Development of Electroplated Magnetic Materials for MEMS

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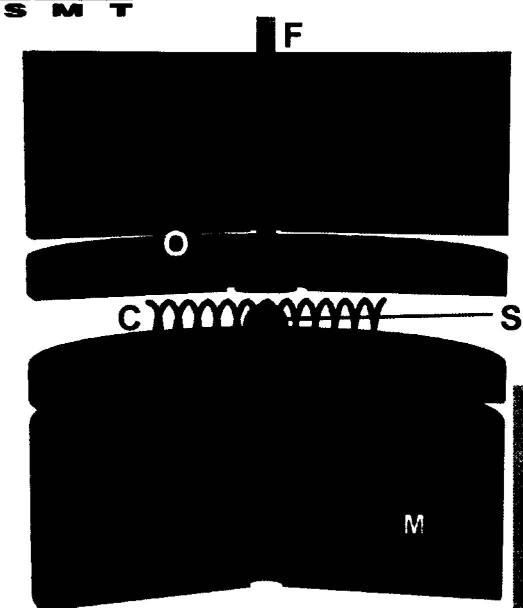
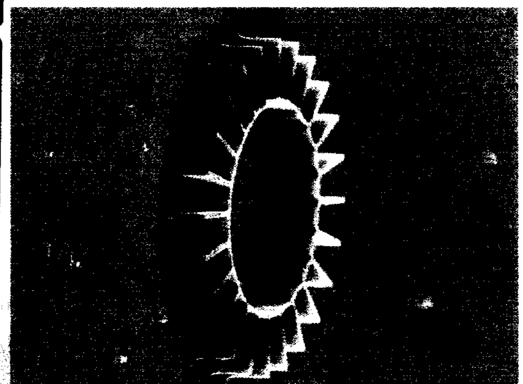
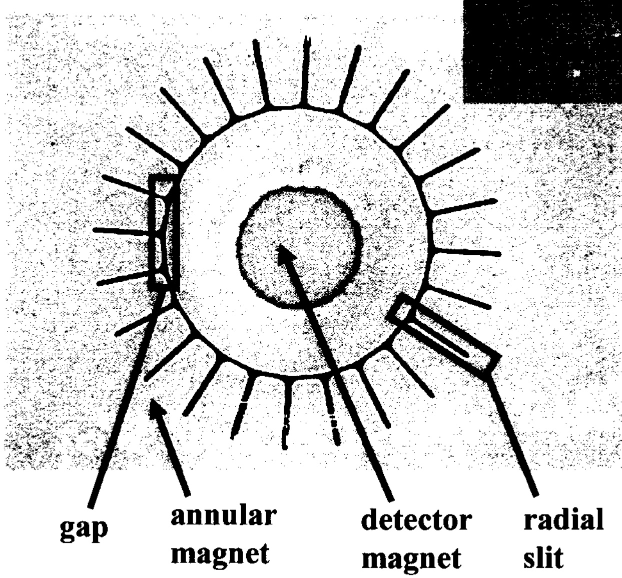
Overview

- Examples of magnetic MEMS
- Electrodeposited soft magnetic materials
- Electrodeposited hard magnetic materials
- Nanoengineered magnetic materials
- FDNMR

JPL's Force-Detected NMR Spectrometer







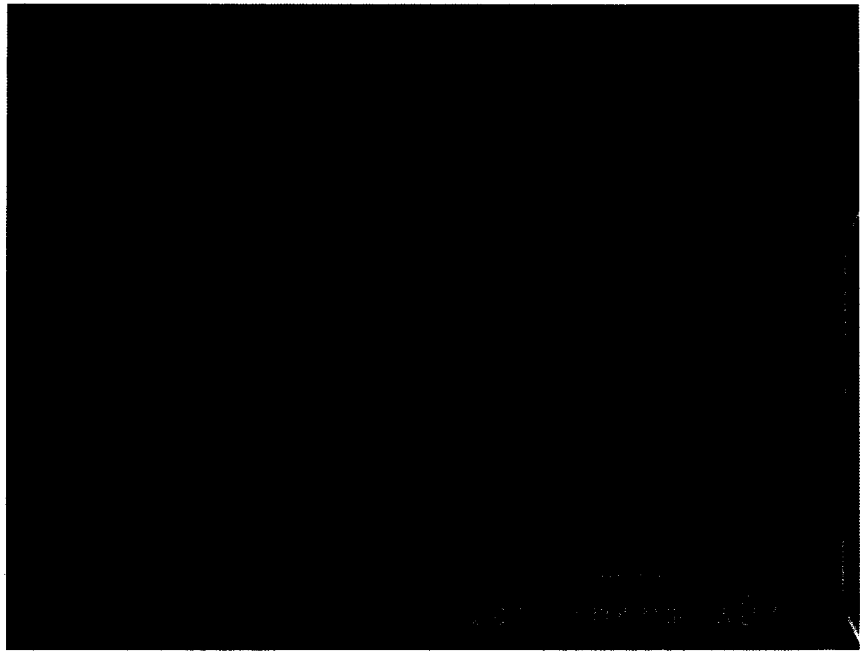
Force-Detected NMR for *In-Situ* Ananlysis

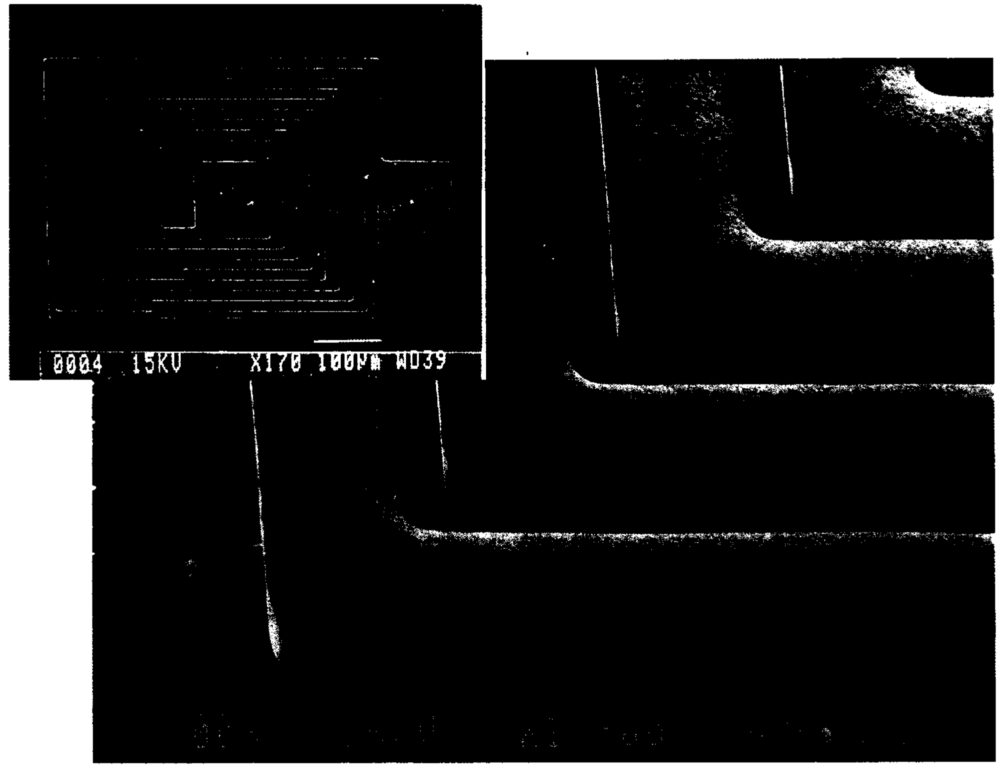
- Study single crystals, organic layers, and mineral phases from corers and drills
- Lightweight, low power;

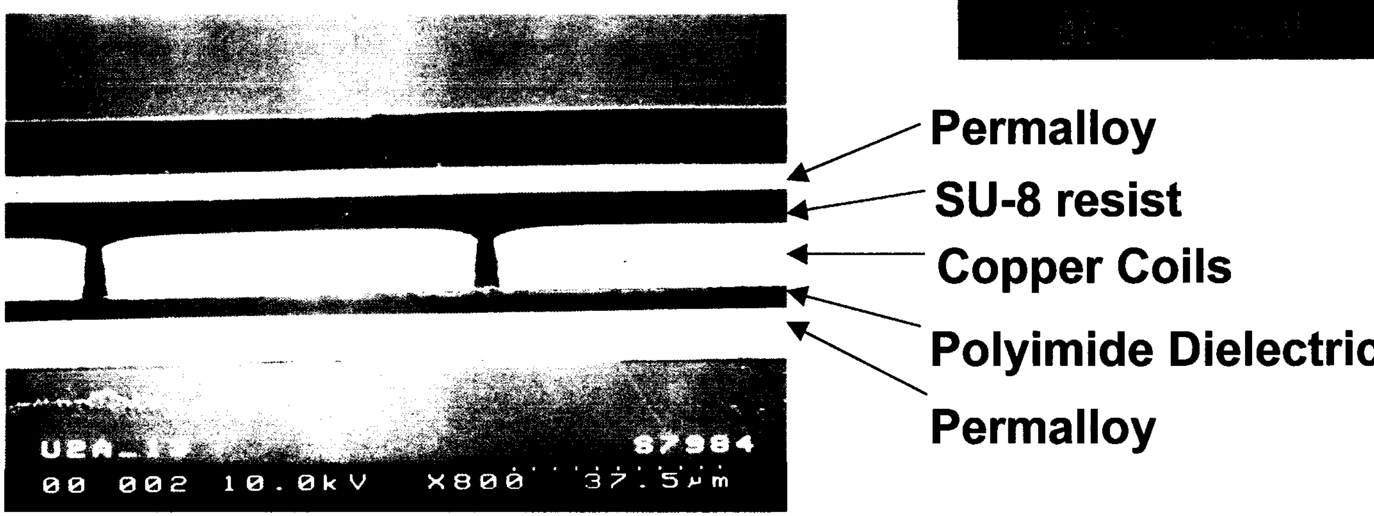
  Can include multiple devices on one vehicle, or deploy in penetrators
- MEMS fabrication produces many devices at once ;

  Easy redundancy and feasible parallel analysis on and off earth

JPL's microinductor

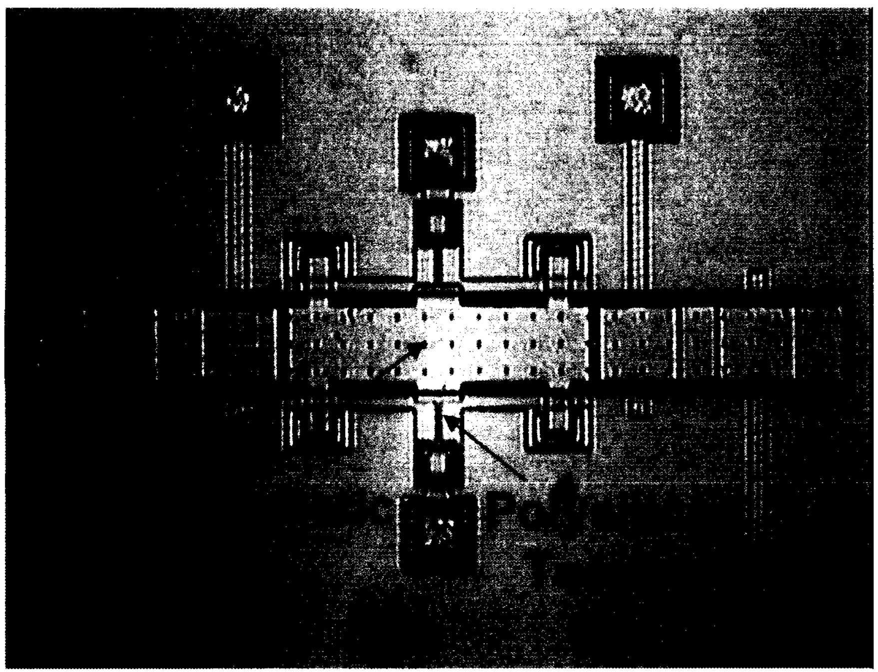


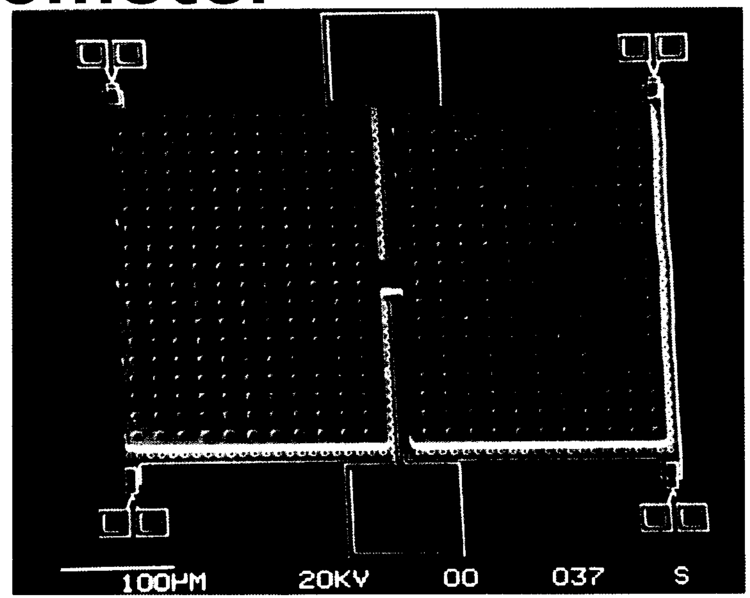


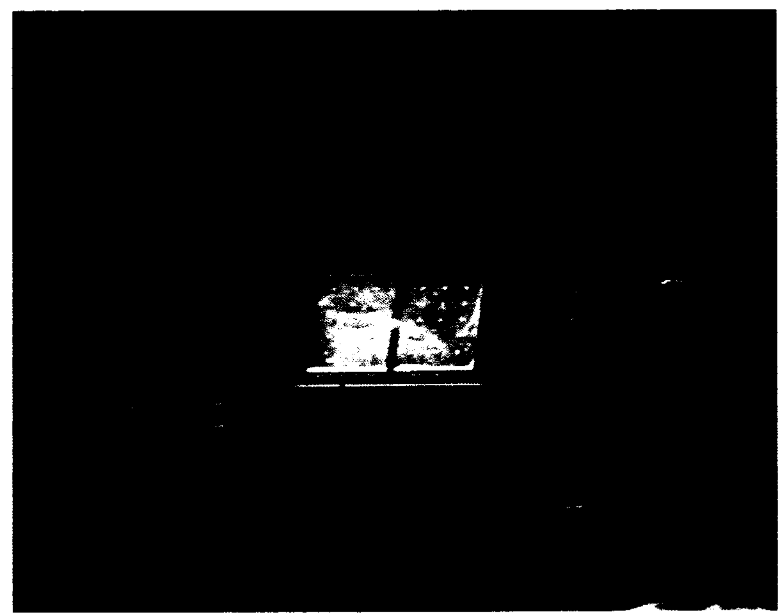


UCLA Low Power Shock Resistive MEMS Magnetometer

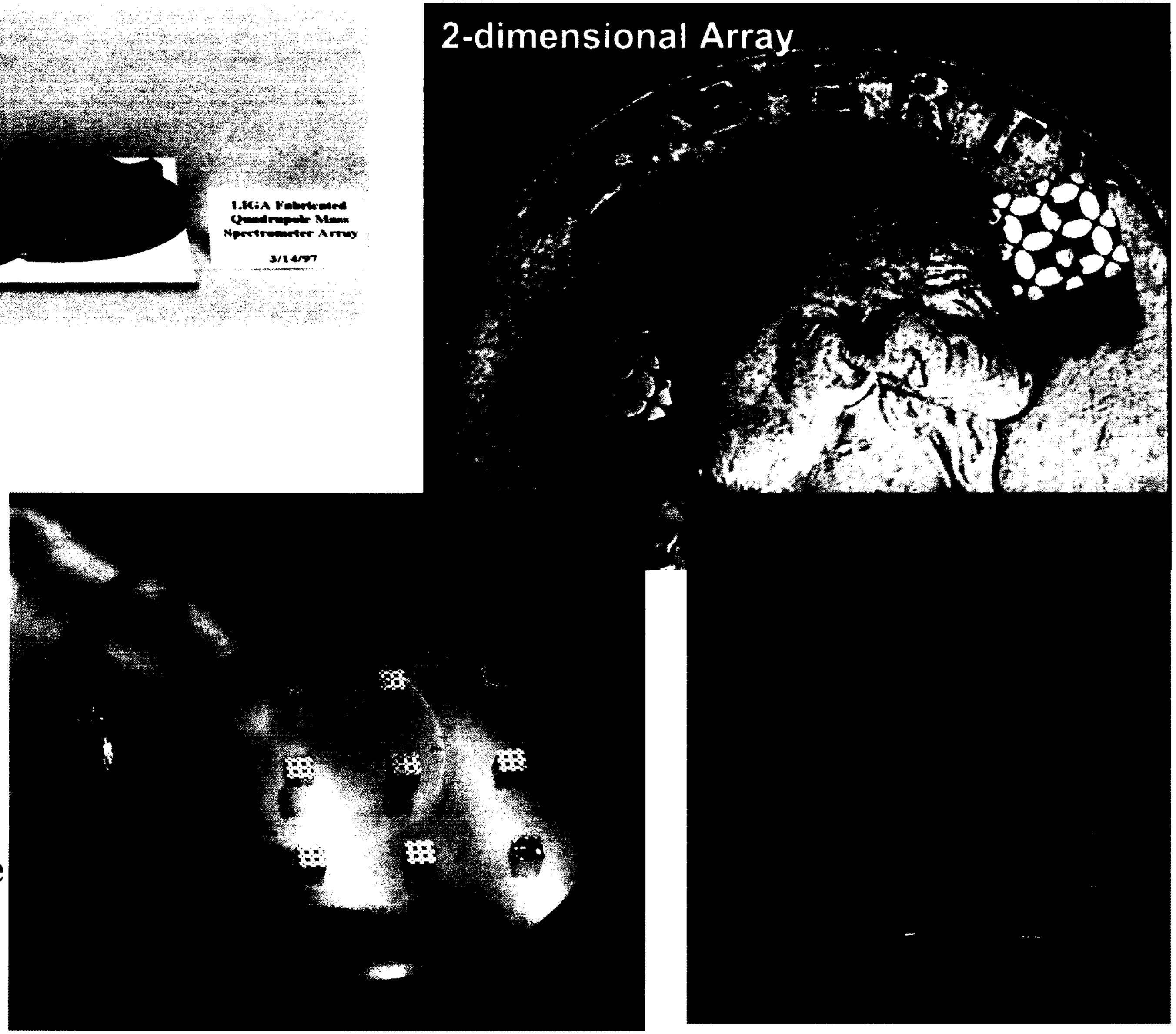
MUMPs fabricated torsion beams and plates with electroplated Magnetic Materials. Pictures taken after full release of the chip.







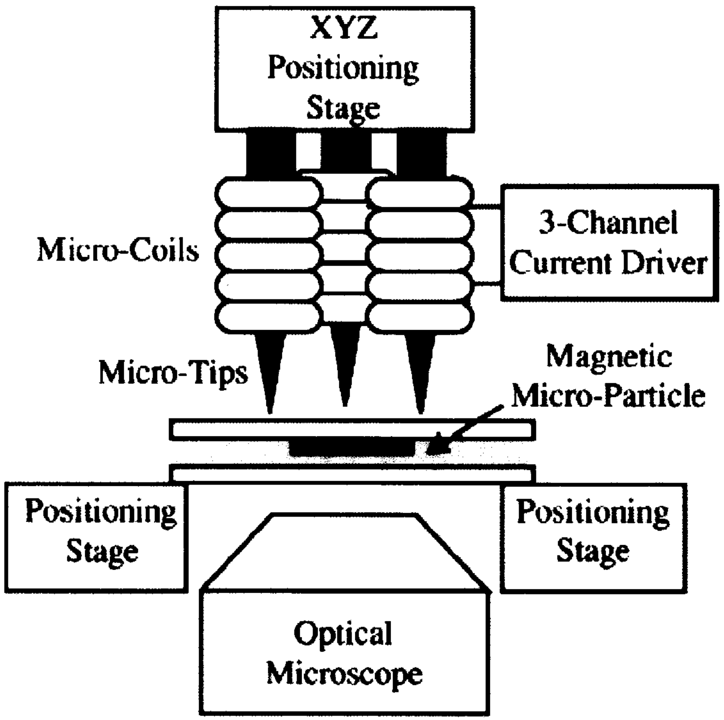
JPL's LIGA Fabricated Quadrupole Mass Filter for Miniature GC/MS



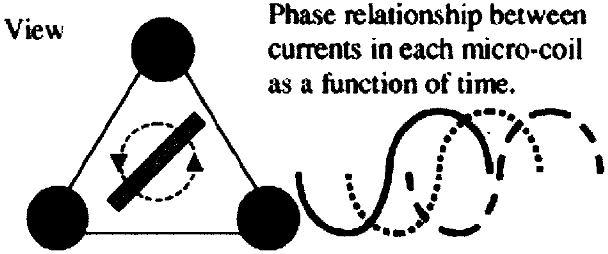
Pole Length: 3 mm pole
# of poles : 24 poles
# of quadrupole: 9 Quadrupole

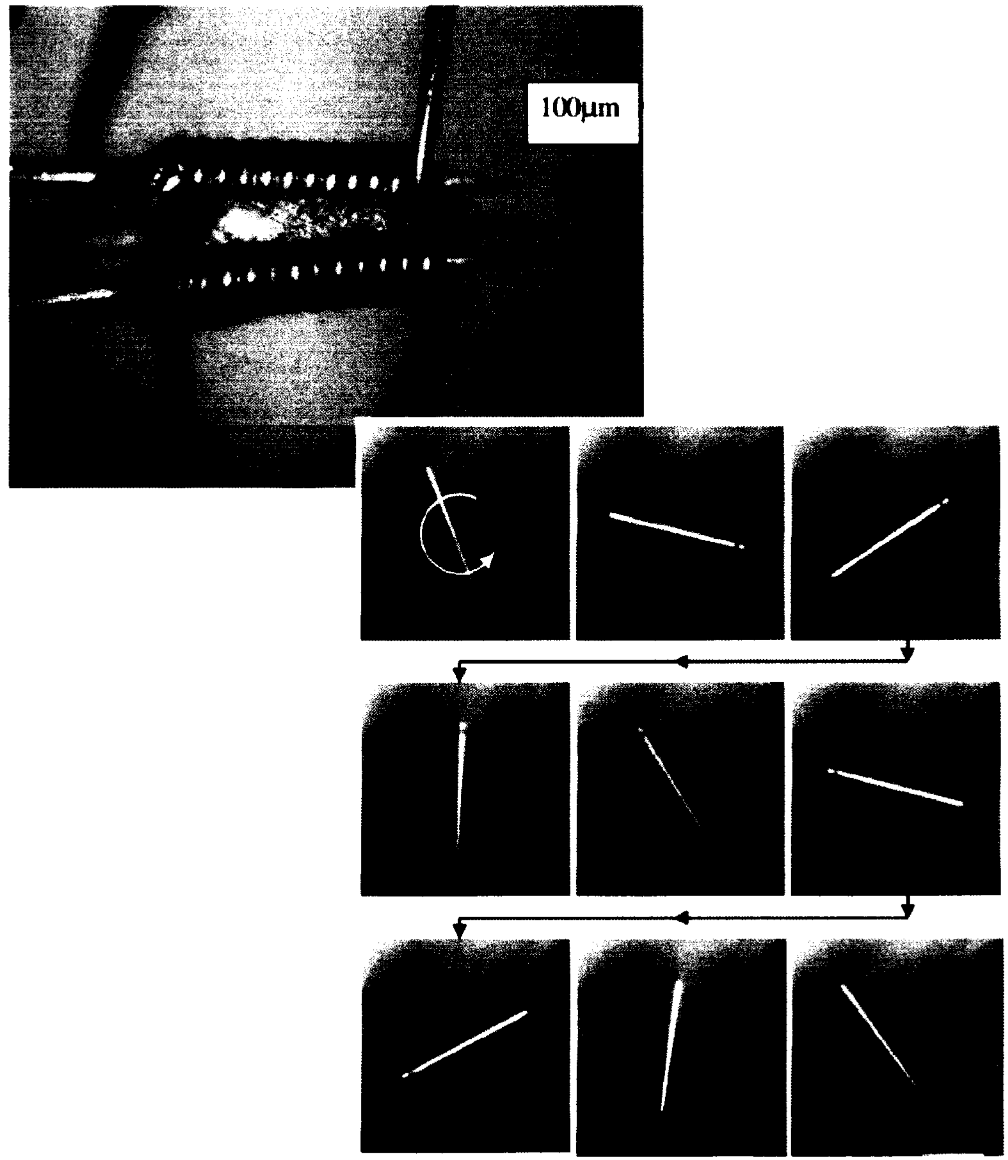
Electromagnetic Micromotors for Microfluidics Application

(a) Side View



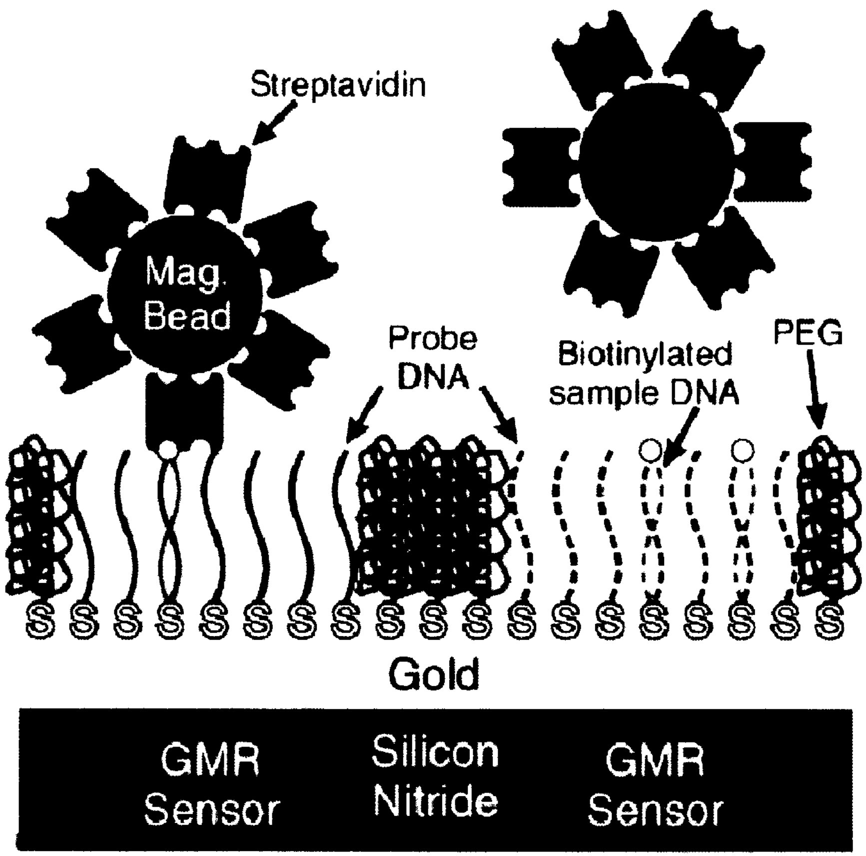
(b) Top View



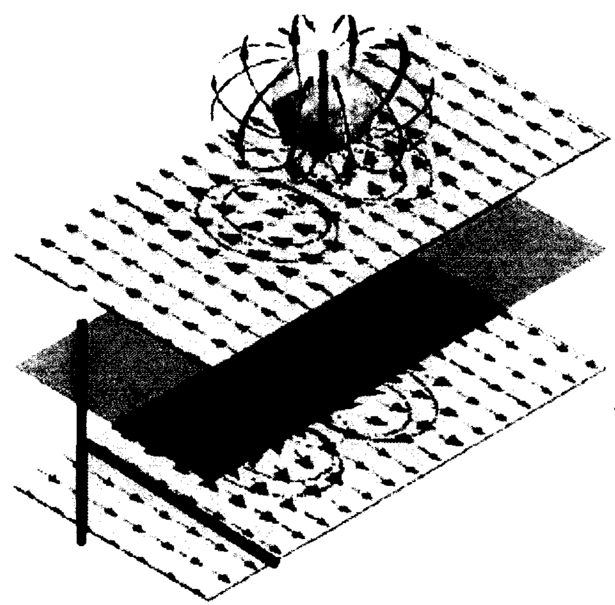


Barbic et al. Appl. Phys. Lett. 79(9),1399 (2001)

Magentic Biosensors



- Small magnetic particles used to "tag" a biological or chemical agents



Worked by NRL

Requirements for Magnetic MEMS

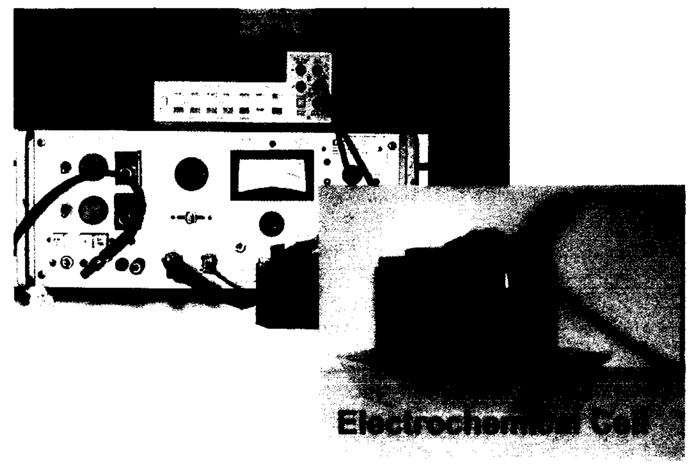
- Good Magnetic Properties
- Good Adhesion
- Low Stress
- Thermal Stability
- No contamination ICs
- Corrosion Resistance (i.e. HF)
- Ability to deposit variable thicknesses
  - (submicron to mm)

Why Electrodeposited Magnetic Materials ????

FLEXIBILITY

• Room Temperature, Ambient Pressure

LOW-COST



• Easily scaled up
• Lower energy requirement
• Low equipment costs
• Lower production costs

QUALITY

•Tailored magnetic properties by controlling microstructure and film composition

Soft Magnetic Materials

Requirements:

- High Magnetic Saturation (M_S)
- Low coercivity (H_C)
- Optimal anisotropy field (H_k) for high permeability
- Good corrosion resistance
- High electrical resistivity (ρ)

ED Iron-Group alloys with high M_S

Material	Magnetic Saturation (T)	Coercivity (Oe)	Magneto-stricition
$Ni_{80}Fe_{20}$	1	0.3	-0+
$Ni_{45}Fe_{55}$	1.6	0.4	+
NiFeCo	0.8-2.4	1	-0+
NiFeCoB	1.5	0.6	
CoNiFeS	1.7	1	+
CoFe	1.9	3	-0+
CoFeB	1	1.9	-0+
CoFeCr	1.7	0.3	-
CoFeNiCr	1.7	0.5	+
CoFeP	1.5	1	-0+
CoFeCu	1.7-2.2	1	-0+
CoFeB (electroless)	1.2	1	
CoB	1.2	1	

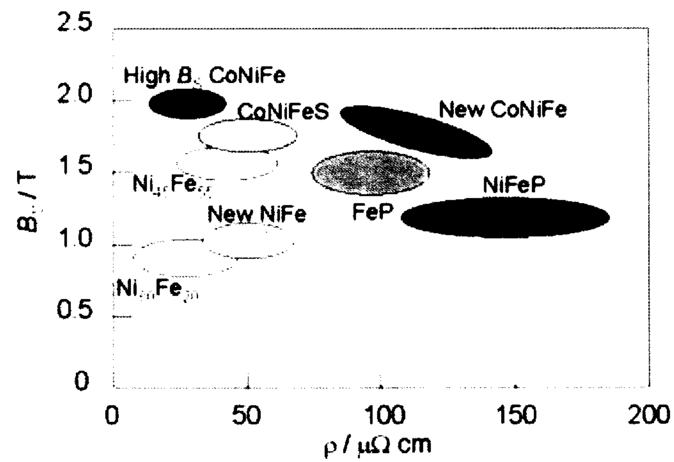
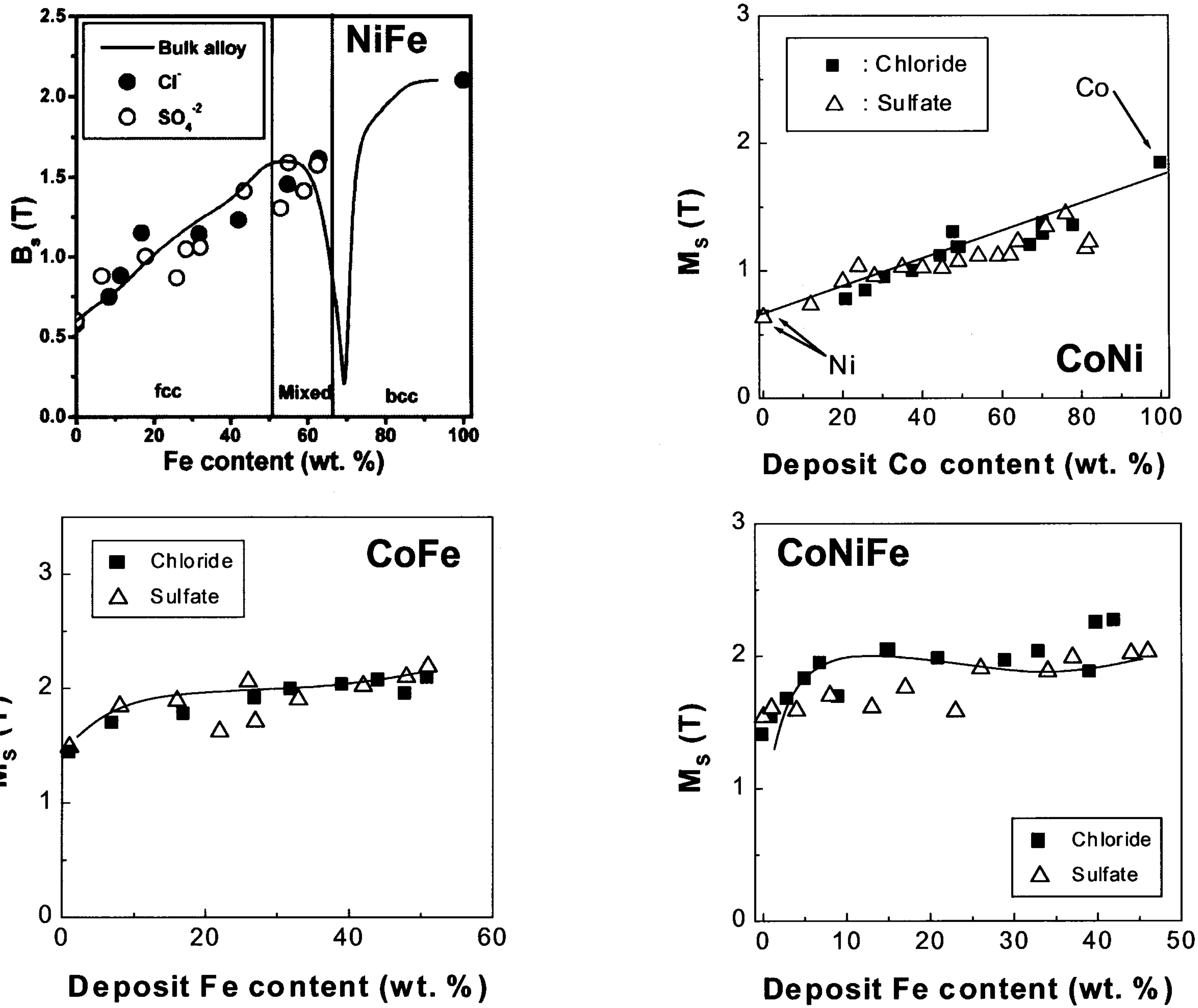


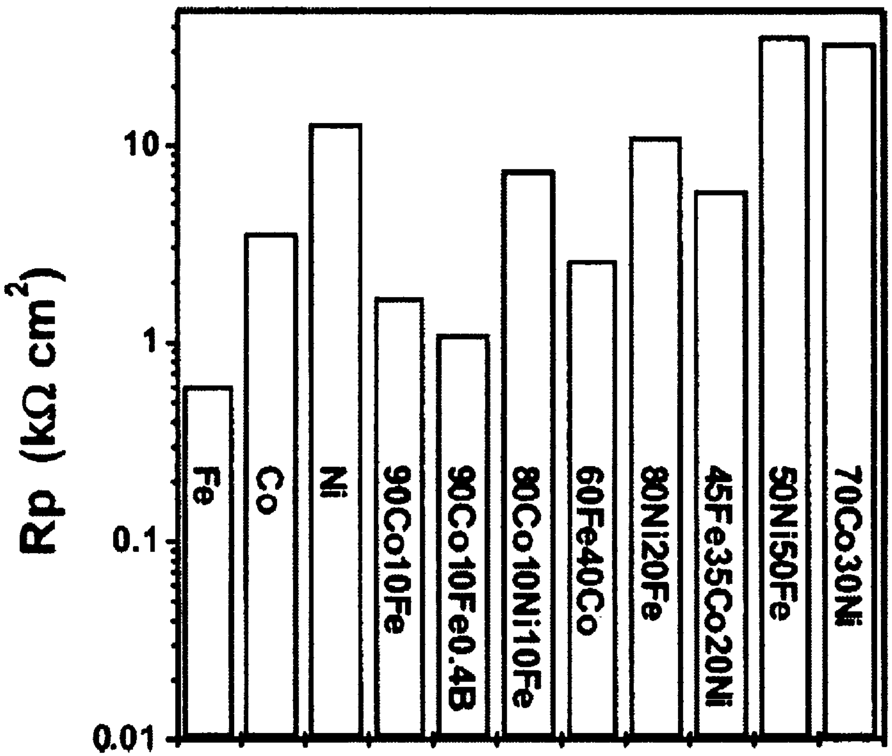
Fig.1 Soft magnetic materials with high *Bs* and high *ρ* mainly developed by waseda group

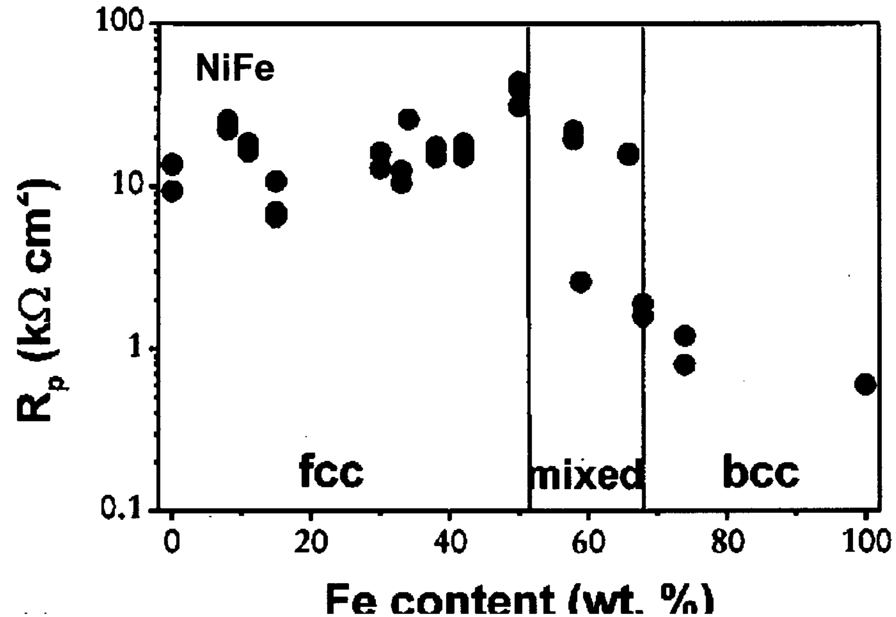
P.C. Andricacos and N. Robertson, IBM Journal of Research and Development, **42**, 671, (1998)

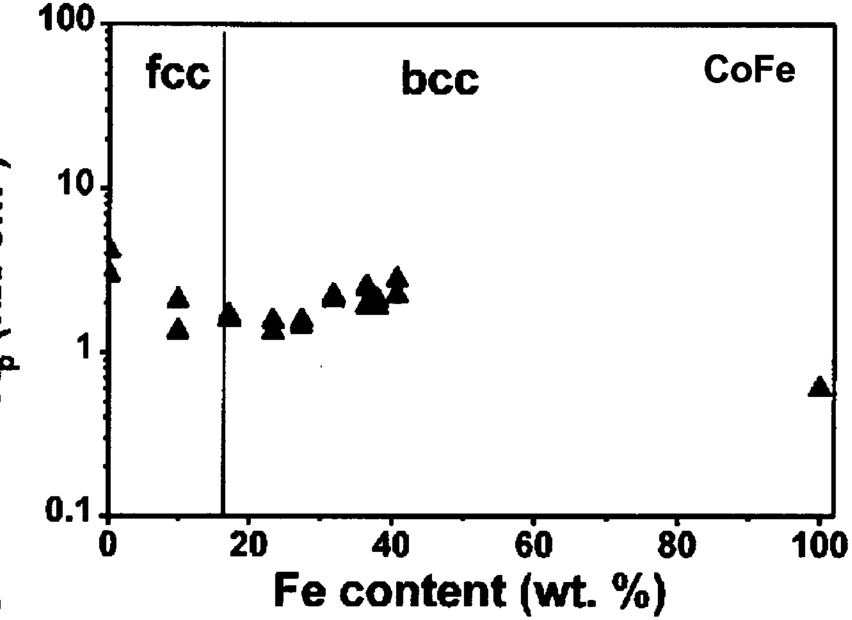
Magnetic Saturation (M_s)



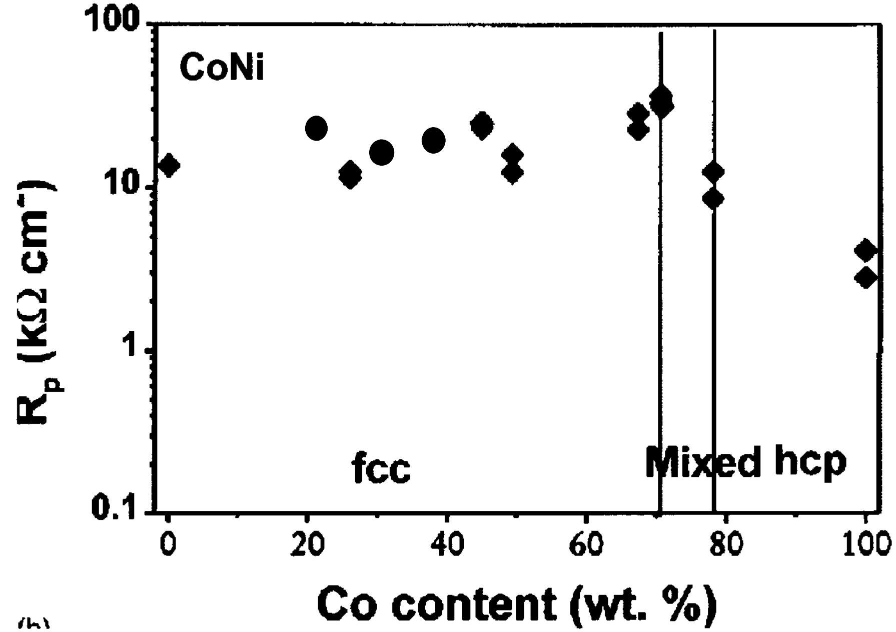
Corrosion Resistance





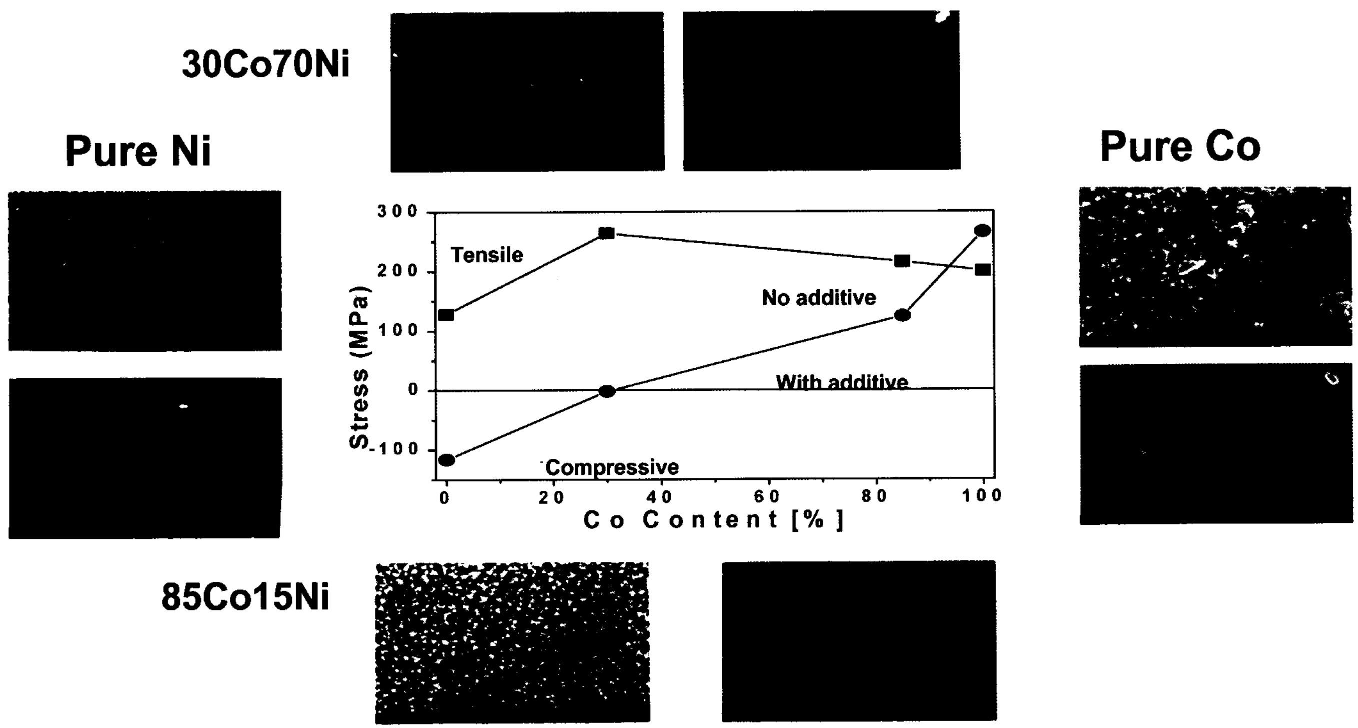


(c)

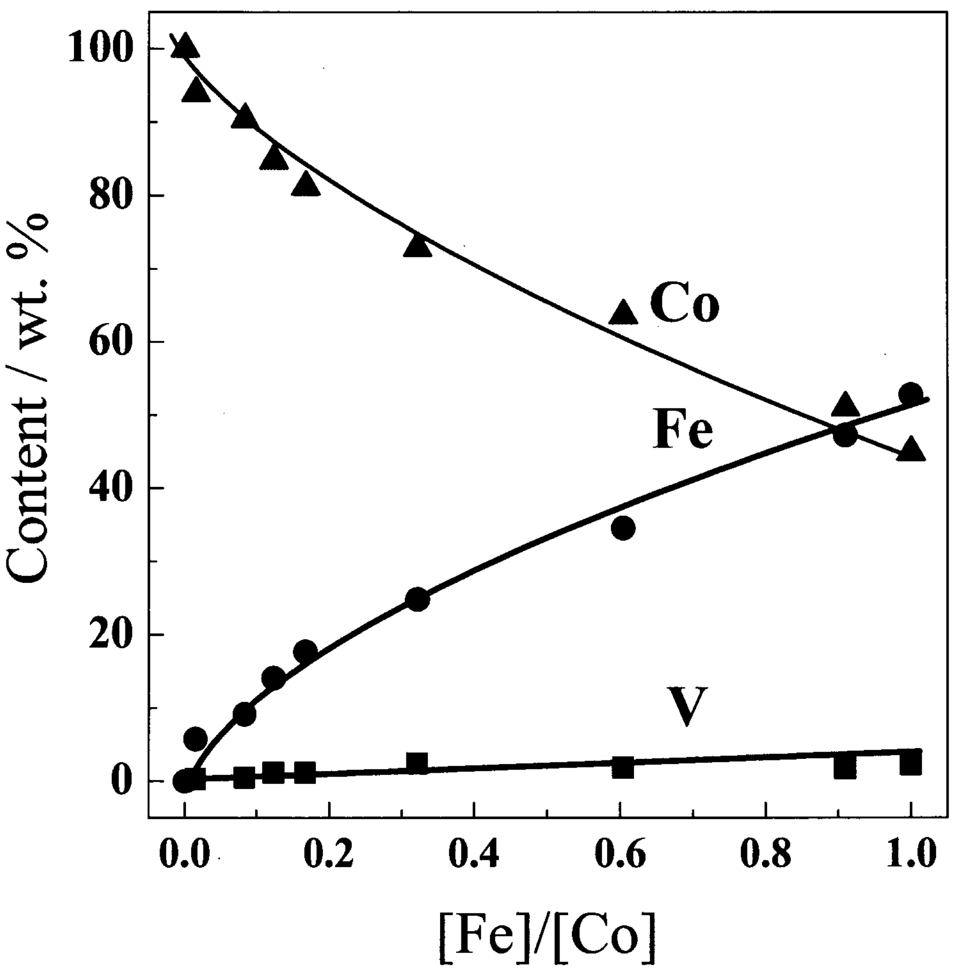


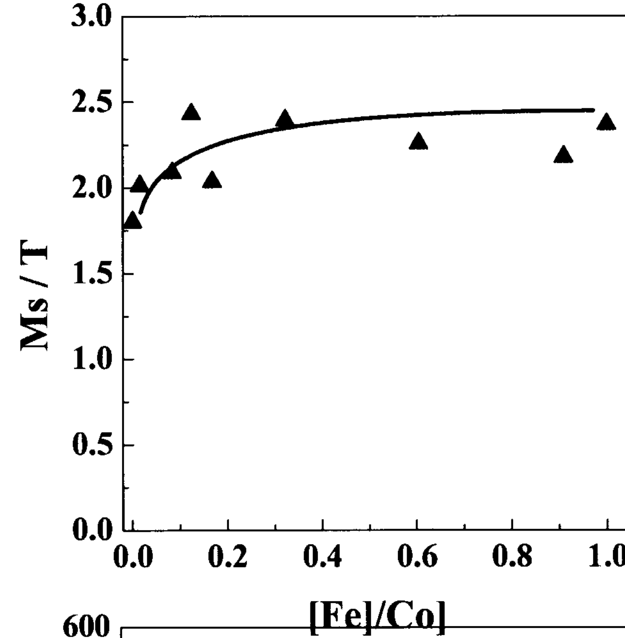
Film stress

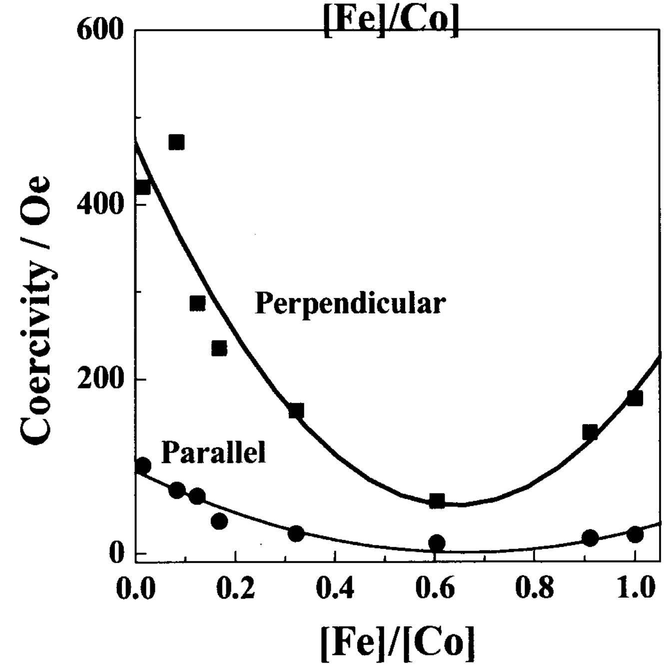
- Generally, film stress increase with Fe content or Co content
- There are many researches on stress reducer for nickel, however not much of work have been done on Co or Fe.



New High Magnetic Saturation Materials Development at UCLA (CoFeV)







Hard Magnetic Materials

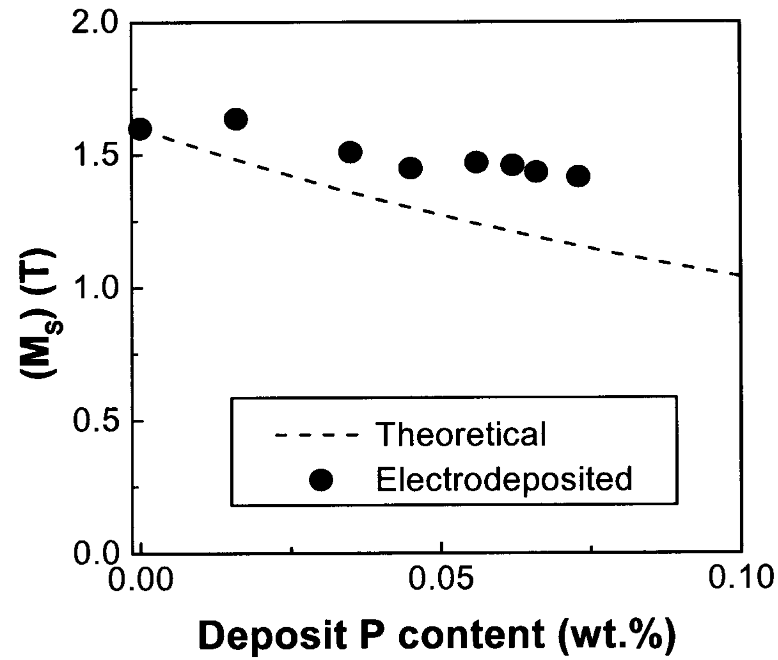
Requirements

- High magnetic saturation (M_S)
- High remanence (M_R)
- High BH product (BH_{MAX})
- High coercivity (H_C)
- High corrosion resistance

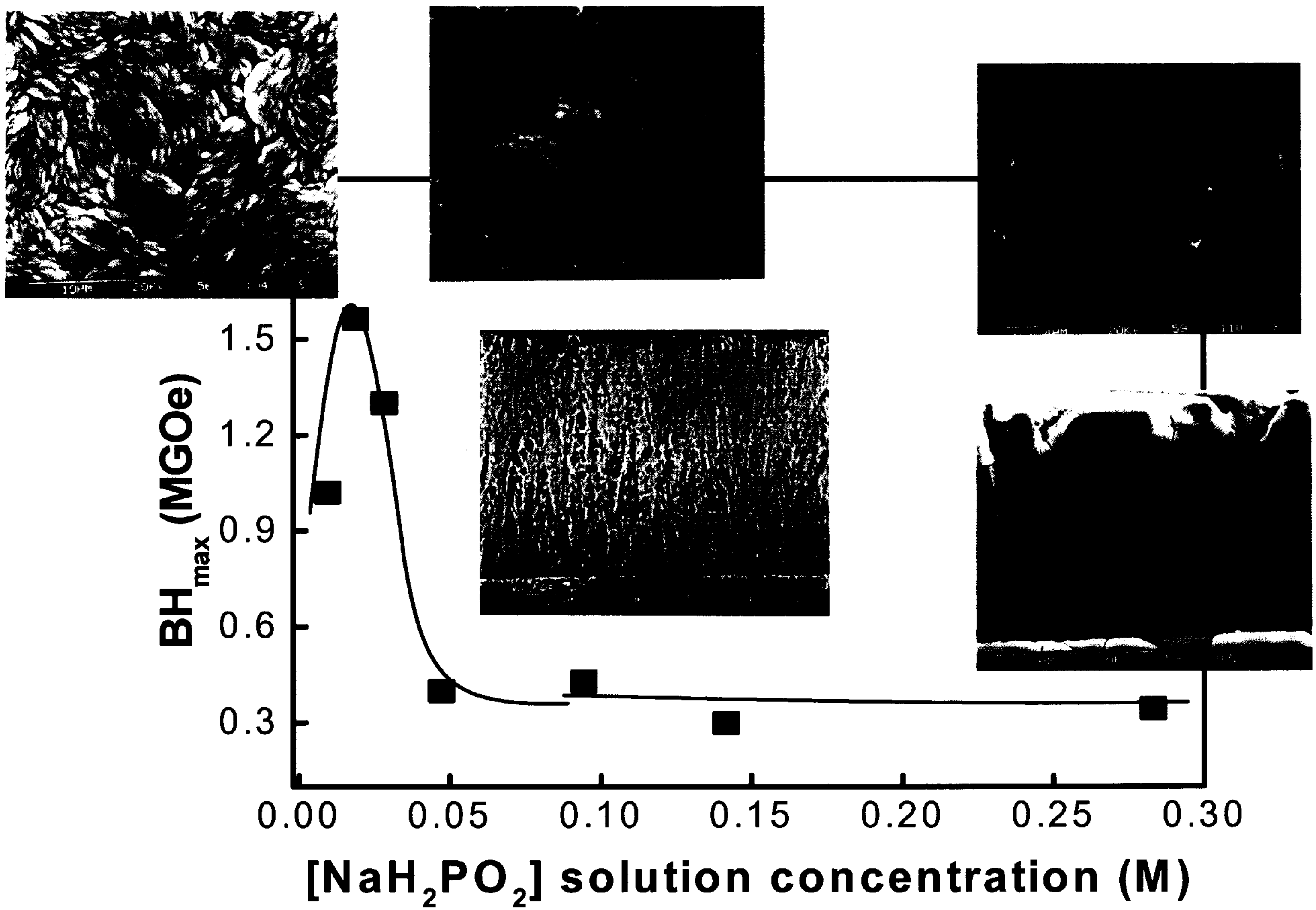
Alloys Elements to Cobalt

VA	VIB	VIII	Others
	P		Cu
Cr	As	Pd	Mn
Mo	Sb	Pt	O
W	Bi		H

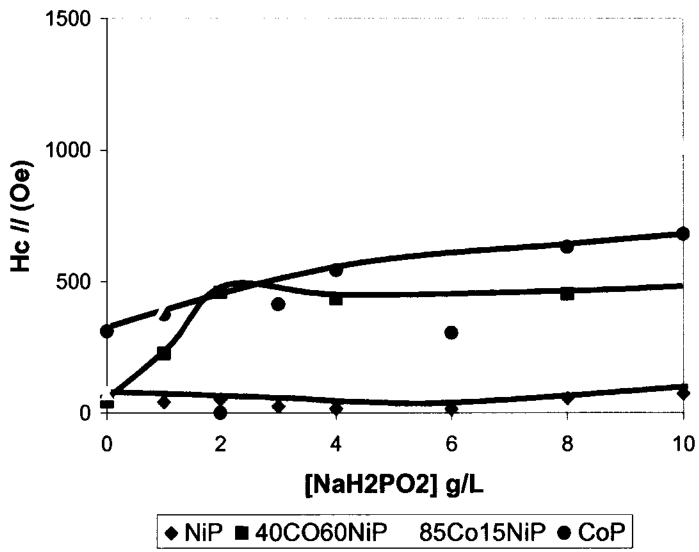
Magnetic Saturation (M_s) decrease with addition of alloying elements



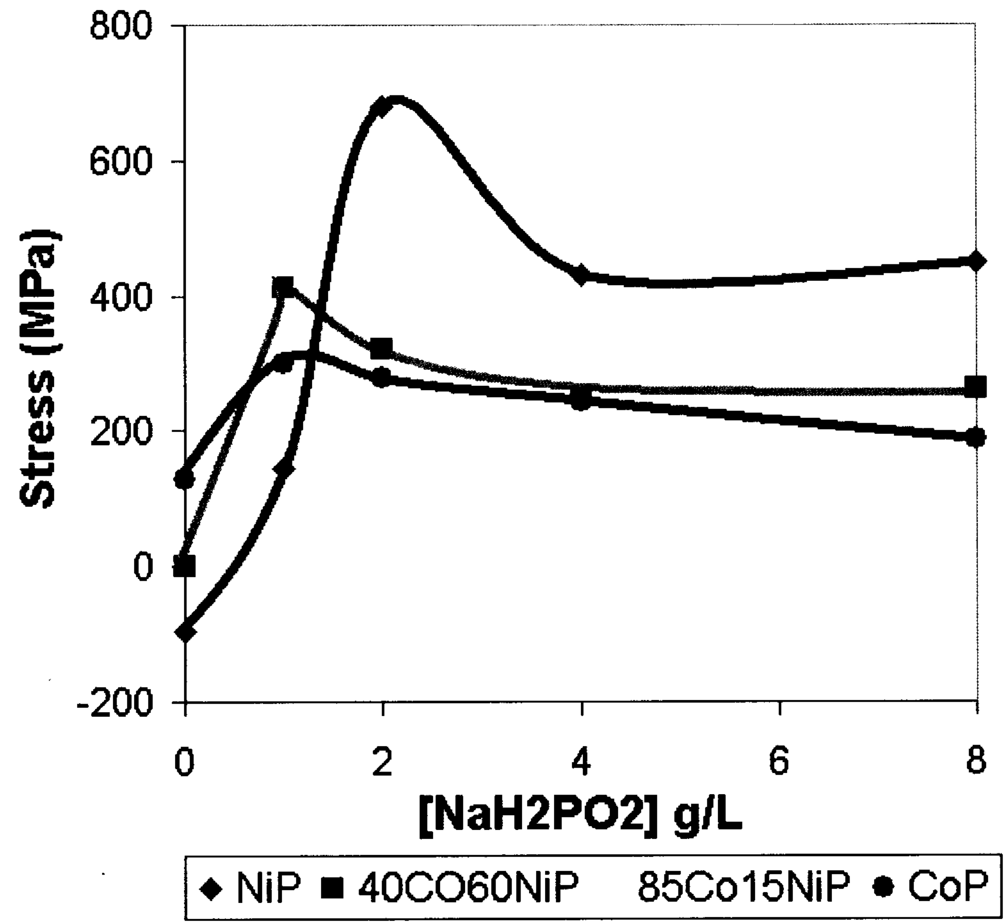
BH_{max} vs. P contents and [Na H_2PO_2]



Film Stress



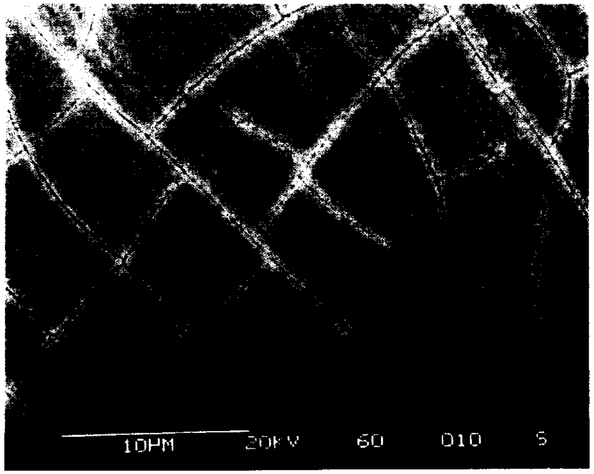
1500
1000
500
0
Hc // (Oe)
0
2
4
6
8
10
[NaH2PO2] g/L
◆ NiP ■ 40CO60NiP 85Co15NiP ● CoP



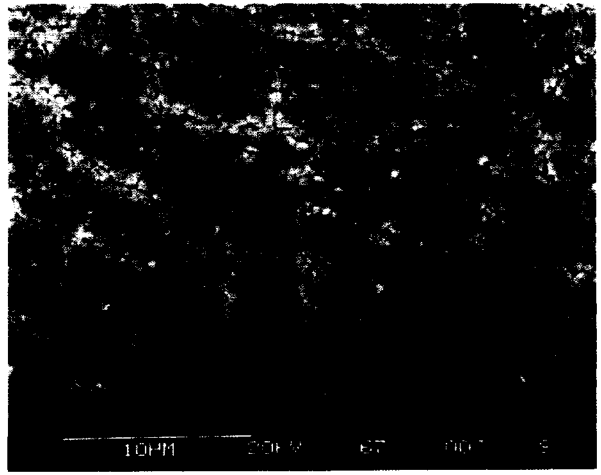
800
600
400
200
0
-200
Stress (MPa)
0
2
4
6
8
[NaH2PO2] g/L
◆ NiP ■ 40CO60NiP 85Co15NiP ● CoP

SEM micrographs

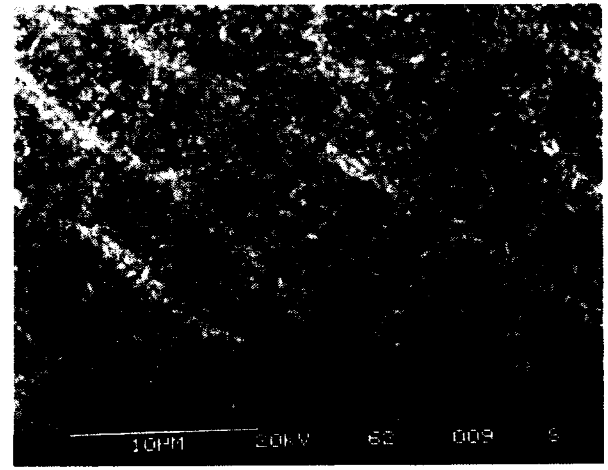
Chloride bath | Sulfamate bath | Sulfate bath



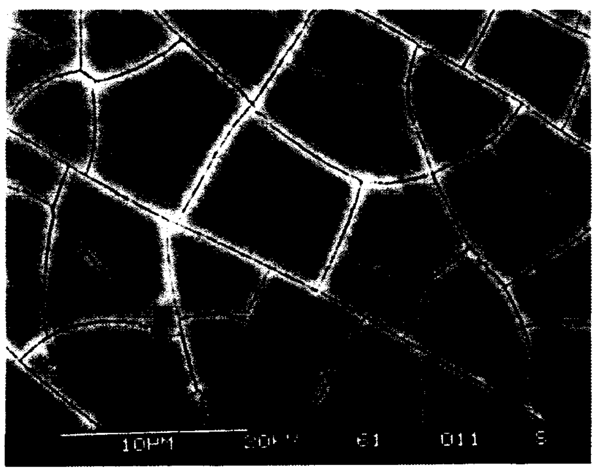
(0.028 M)



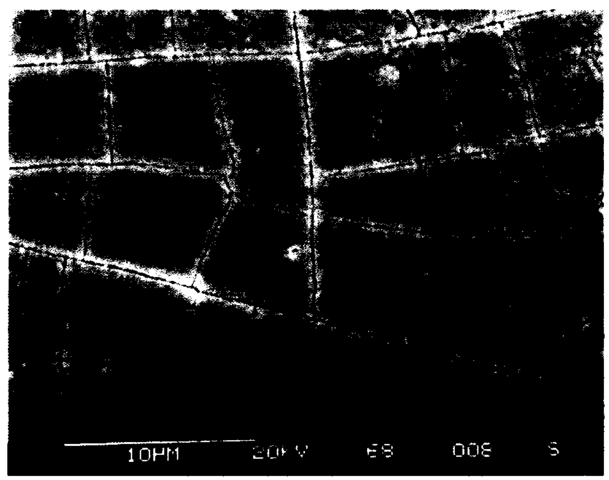
(0.028 M)



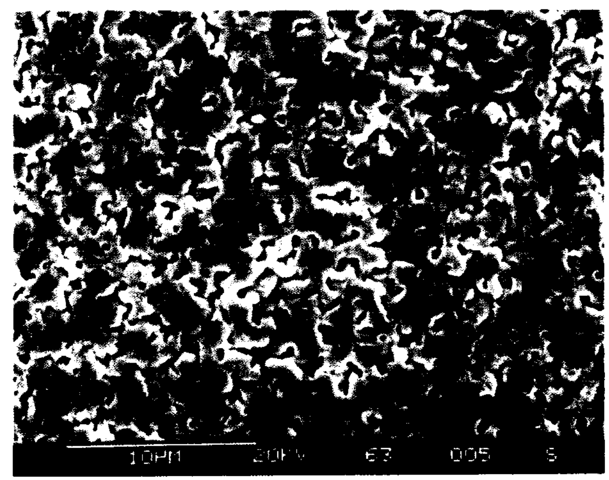
(0.028 M)



(0.142 M)

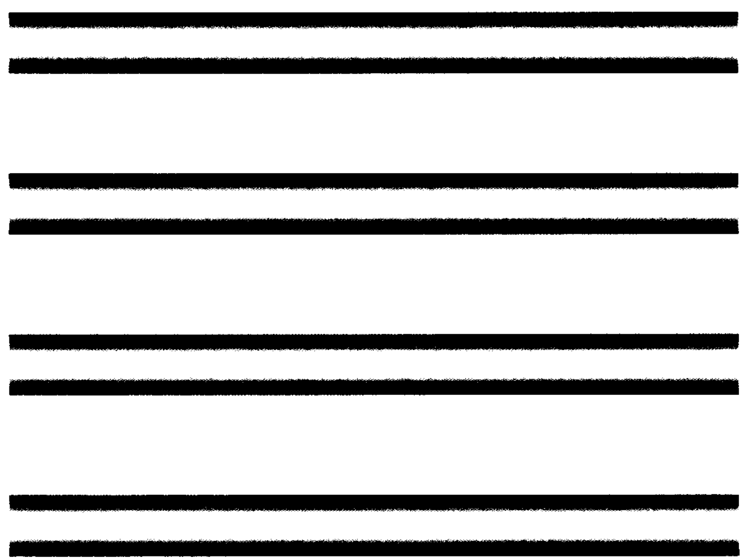


(0.142 M)



(0.142 M)

Film Structuring to Minimize Total Film Stress



- Minimizing the film stress and improve corrosion resistance while maintaining the hard magnetic properties by structuring the magnetic films

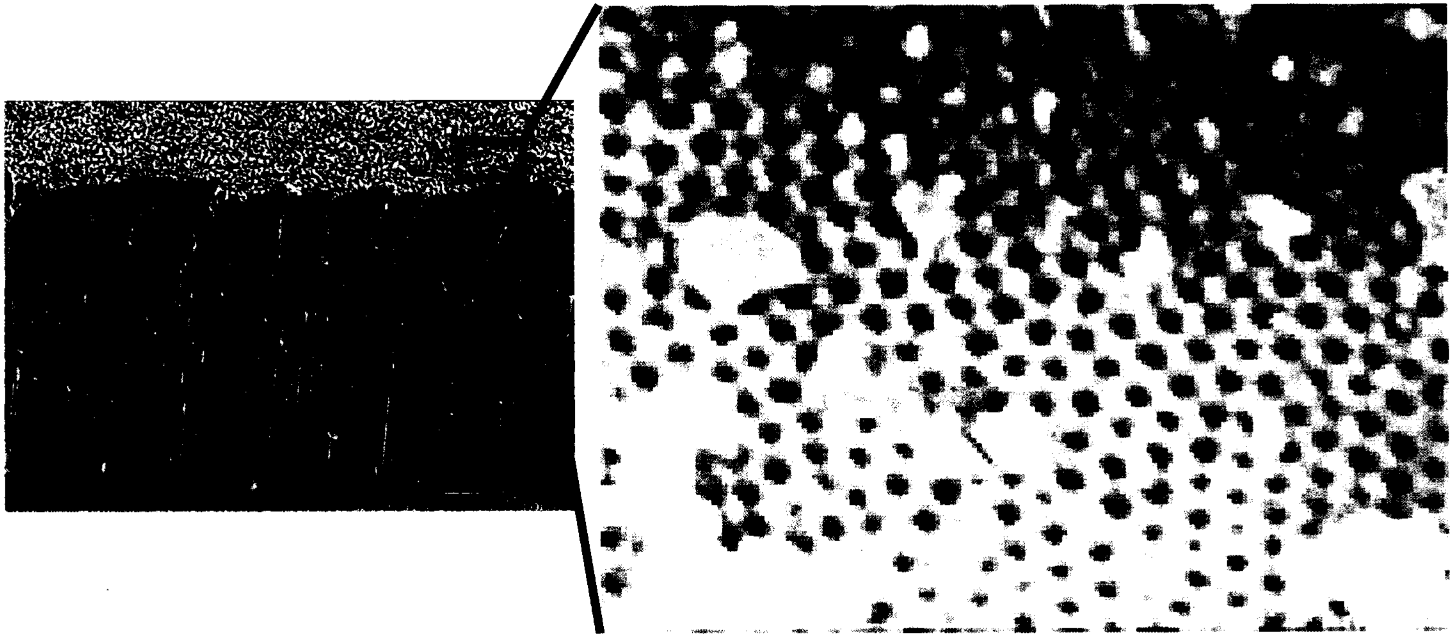
Hard Magnetic Tensile, Low Corrosion Resistance Layer (e.g. CoNiP)

Magnetic Compressive, High Corrosion Resistance Layer (e.g. Ni)

Magnetic Properties of Electrodeposited Magnetic Films

Electrodeposited Alloys	Add Element (wt. %)	Hc (Oe) [Thickness]	Ms (T)	M_R or S
CoNi	20-40 Ni	100 (//), [2 μm]	1.4-1.6	0.6-0.775
CoP	2-4 P	1400 (//), 1300 ($\perp$), [2 μm]	1.5-1.6	0.2-0.5 (//) 0.1-0.3 ($\perp$)
CoNiP	18-37 Ni, 1-3 P	926 (//), 2150 ($\perp$), [2 μm]	1.2-1.4	0.2-0.45 (//) 0.1-0.3 ($\perp$)
CoMnP	2-4 P, <1 Mn	800 (//), 2000 ($\perp$), [2 μm]	1.4-1.5	0.1-0.3 (//) 0.1-0.2 ($\perp$)
CoW	12-44 W	400 (//) [0.1μm]	1.0-1.5	0.2-0.5
Co_3W/CoW	30-40W	250 (//) [2 μm]	1.2-1.3	0.2-0.5
CoPtP	30 Pt* 3 P*	2620 (//), 2940 ($\perp$) [10 μm]	1	0.4-0.6 (//) 0.3-0.4 ($\perp$)
Co/Cu	5-50 Cu	340 (//), 650 ($\perp$) [2 μm]	0.7-1.3	0.6-0.7 (//) 0.1-0.2 ($\perp$)

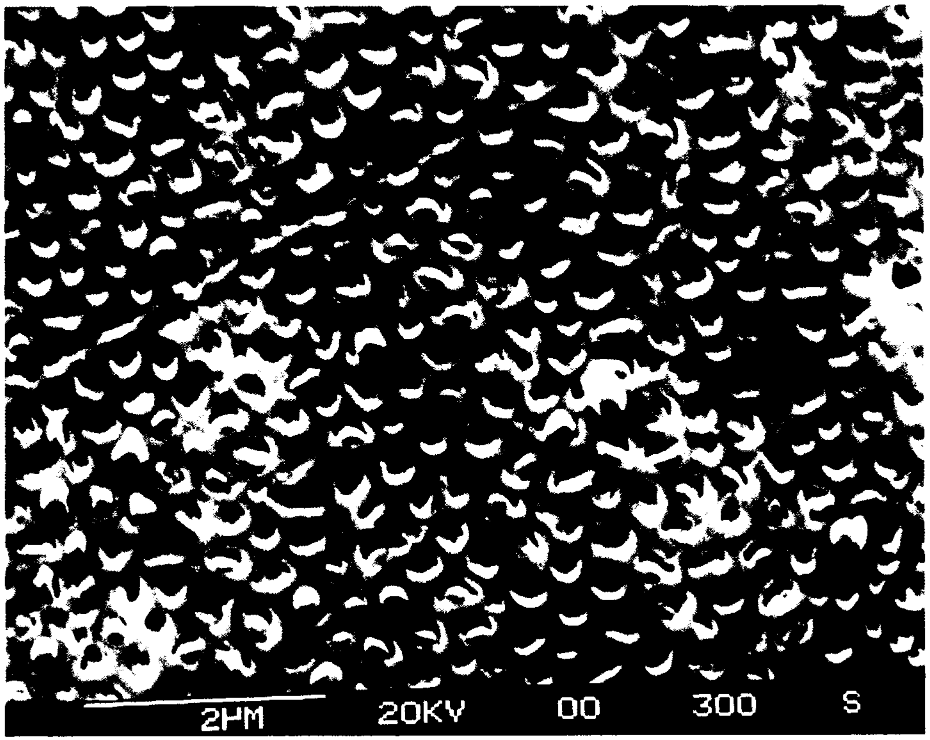
Nano-engineered Materials

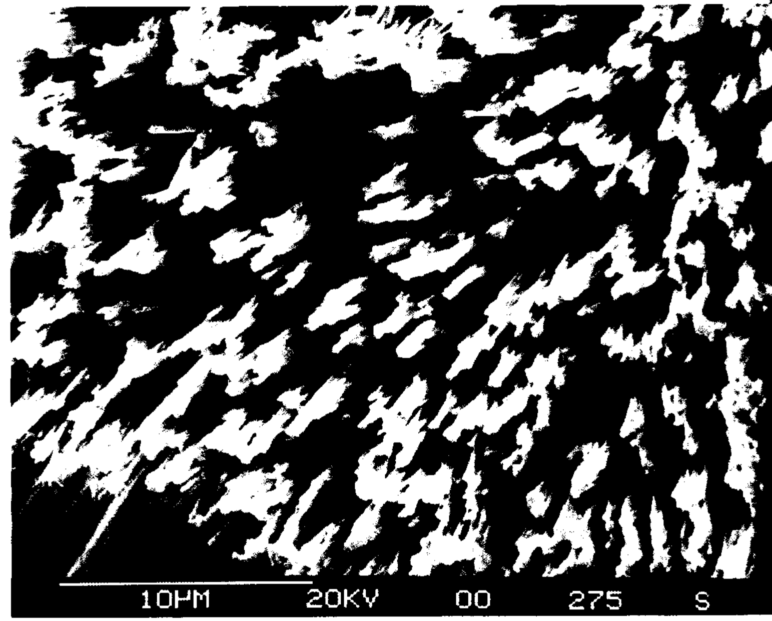


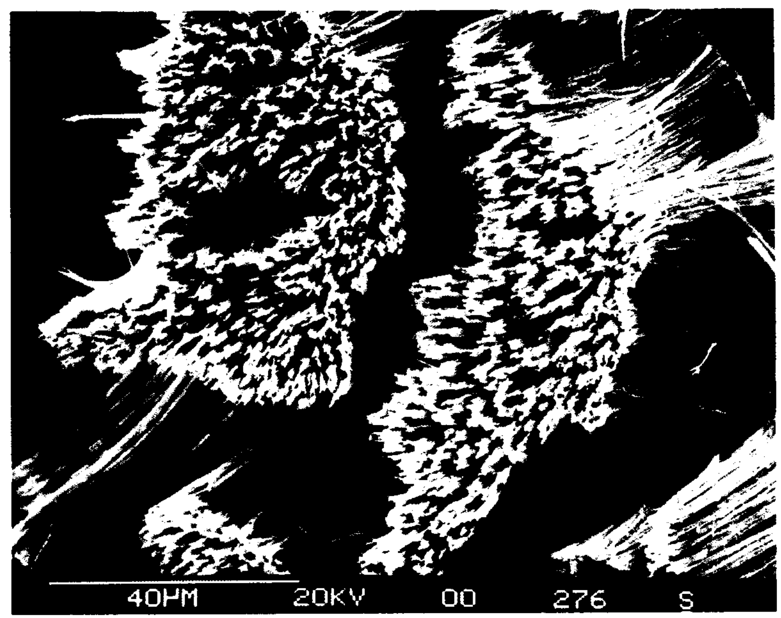
- Nanoengineered magnetic properties
  - Magnetic properties strongly influence by size in nanoscale
- Filled the nanotemplate with magnetic materials to produce
  - nanowires, nanodots, CPP GMR nanostructured nanowires

CoNiP

Filled Aluminum Template with Magnetic Material

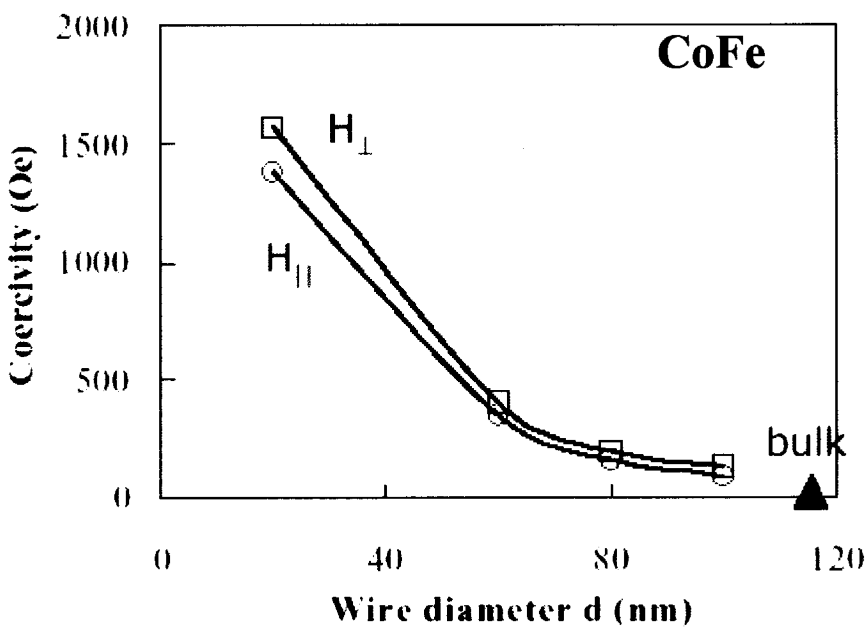


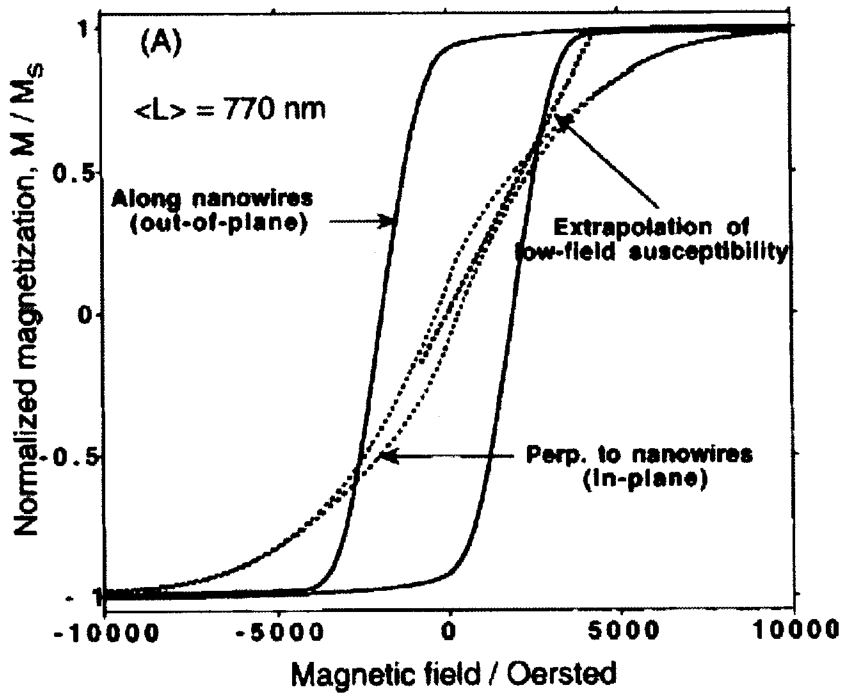




Nanoengineering magnetic properties

- Coercivity increase with decrease in nanowire diameter (finite size effect)
- Squareness increase with decrease in nanowire diamte (shape anisotropy)

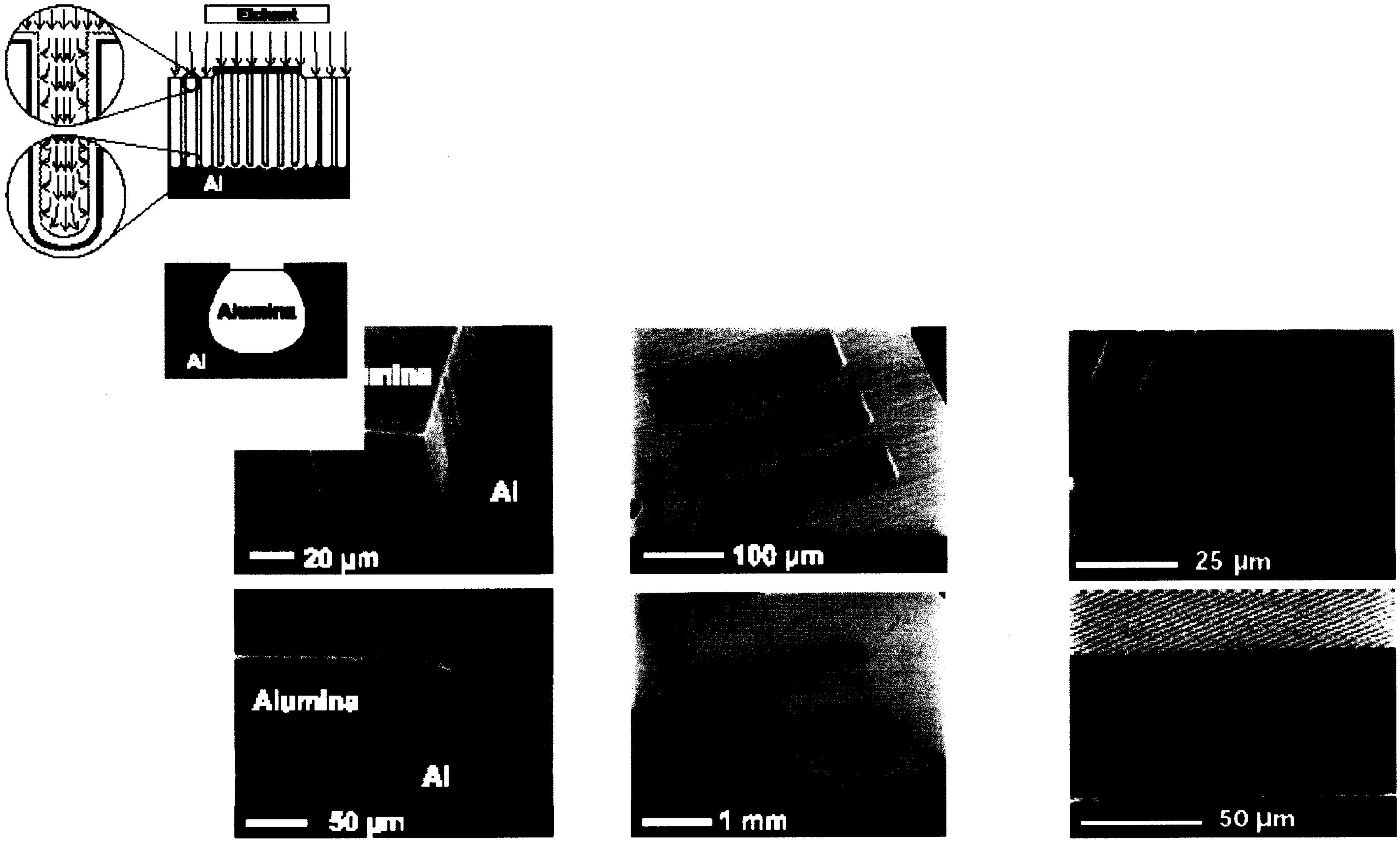




R. M. Metzger et al. IEEE Trans Magn. 36, 30-35 (2000).

John Hopkins University

Magnetic Material-Ceramic Composites MEMS



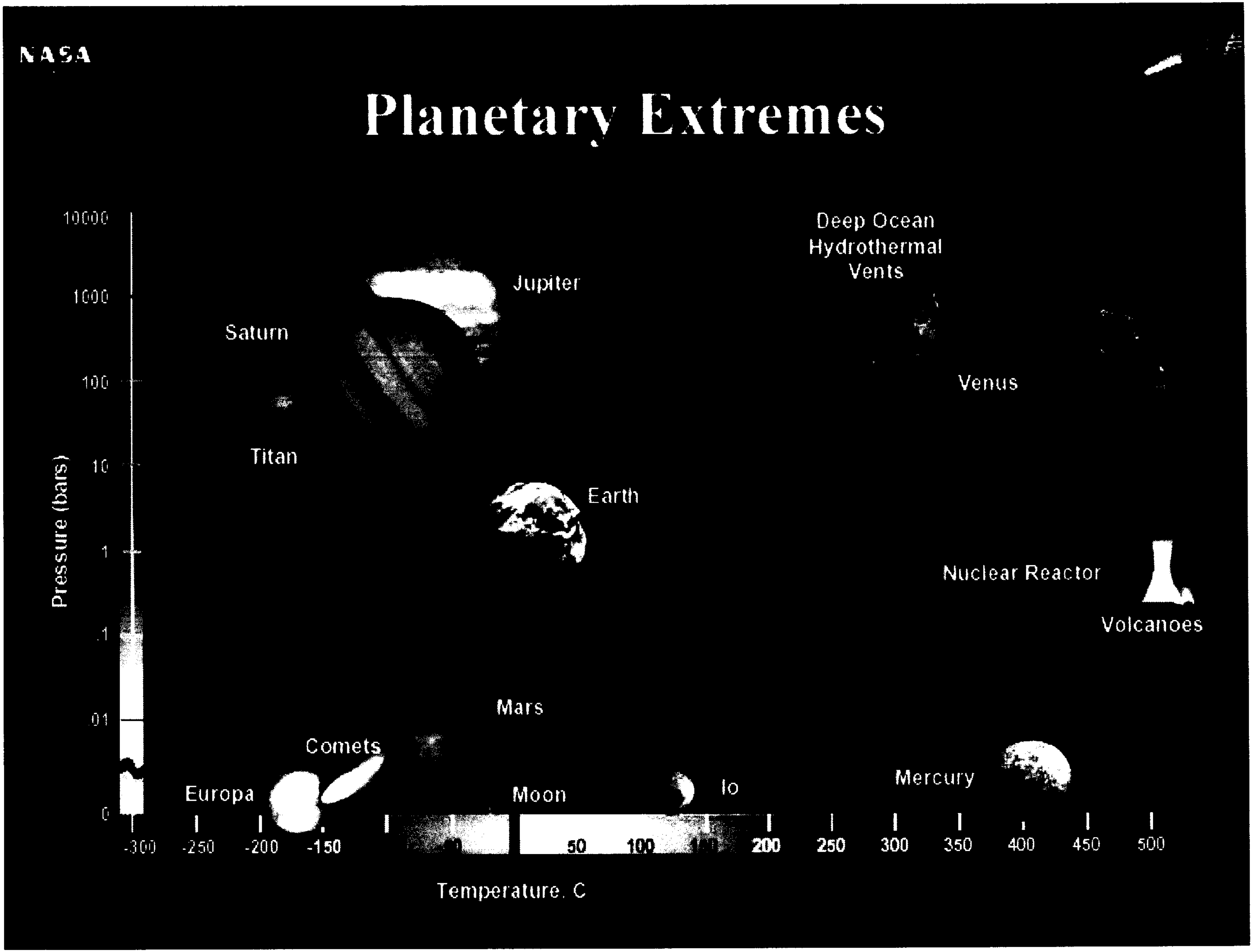
D. Routkevitch, Nano Materials Research LLC. www.nrcorp.com

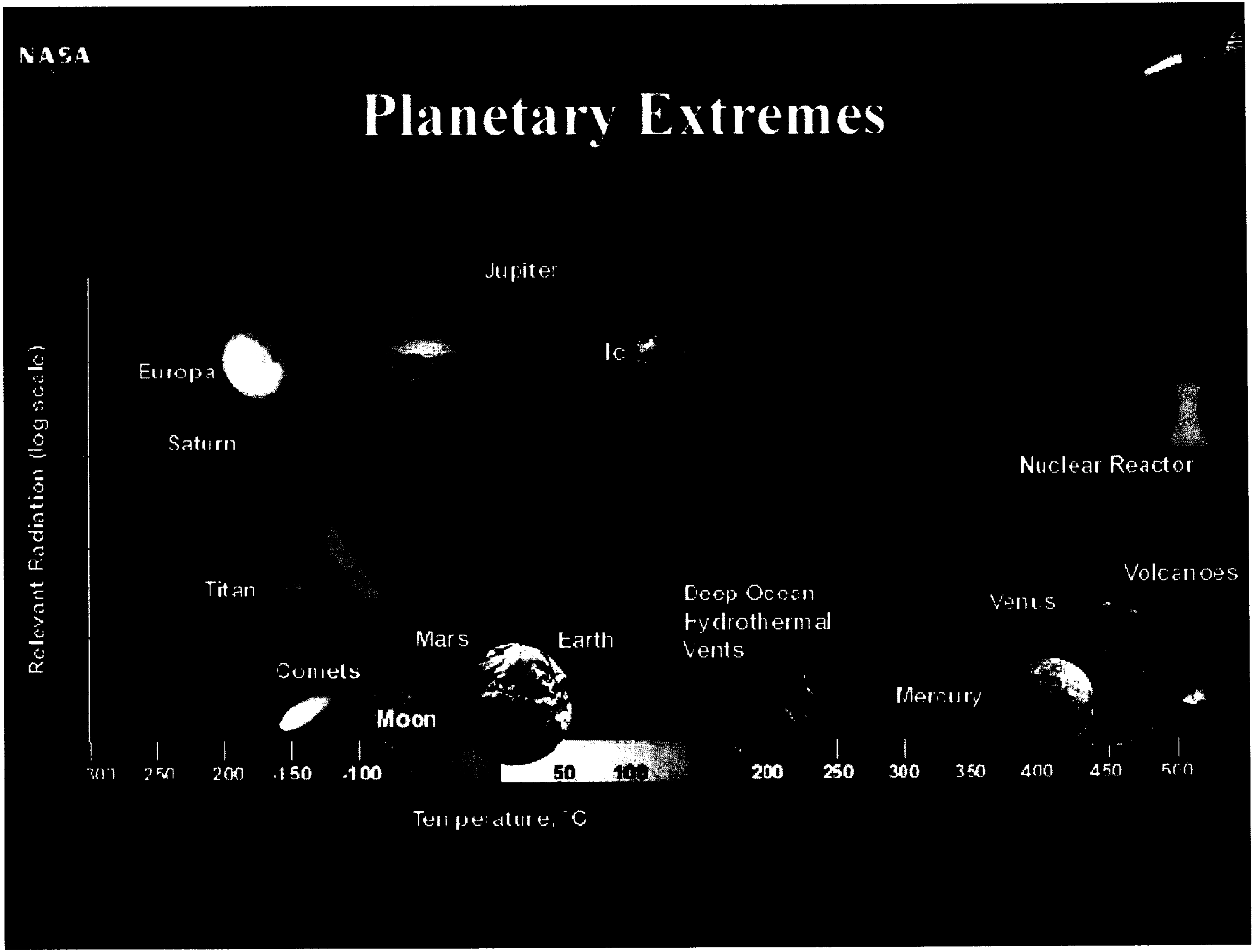
NASA Needs

- Size, mass and power consumption for devices and instruments are severely constrained on space missions.
- Given the prohibitive costs of launching any payload into space (between \$10,000 - \$1000,000 per kg, depending on the type of mission), the trend during the past decade has been towards "smaller, faster and cheaper" space missions. Such missions are necessarily of the "micro-spacecraft" class (under 100 kg mass).

Some Important Considerations for In situ Instruments Used in NASA Applications

- Low Power
- Low mass
- Low volume (for space applications)
- High reliability
- Long lifetime (sometimes as long as a decade)
- Manageable data rate
- Easily calibrated
- Must have compatible sample handling mechanisms
- Able to withstand extreme environments
- Able to withstand launch loads


NASA
Planetary Extremes
Deep Ocean Hydrothermal Vents
Jupiter
Saturn
Venus
Titan
Earth
Nuclear Reactor
Volcanoes
Mars
Comets
Europa
Moon
Io
Mercury
Pressure (bars)
10000
1000
100
10
1
.1
.01
0
-300
-250
-200
-150
50
100
200
250
300
350
400
450
500
Temperature, C



NASA
Planetary Extremes
Jupiter
Europa
Io
Saturn
Nuclear Reactor
Titan
Volcanoes
Deep Ocean Hydrothermal Vents
Venus
Mars
Earth
Comets
Mercury
Moon
Relevant Radiation (log scale)
300
250
200
-150
-100
50
100
200
250
300
350
400
450
500
Temperature, °C

Motivation

Nuclear Magnetic Resonance (NMR) Spectroscopy

•Highly specific chemical information:

identification of atomic elements, chemical bonding & reactions

• Can detect ^1H and light nuclei;

detection/distinction of H_2O & organics as well as minerals

• Non destructive to sample

• Imaging down to micron scale and below

• Higher sensitivity with force detection than Faraday-law detection at 0.5 mm length scale and below

↓

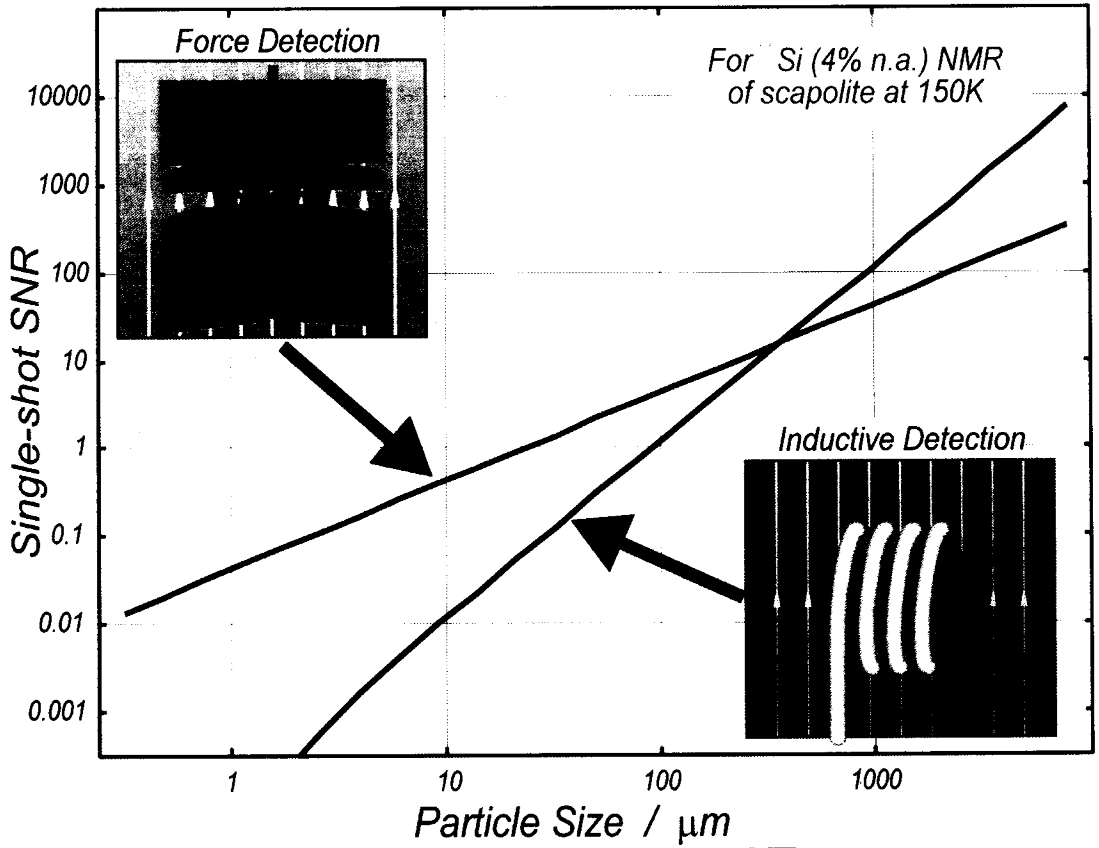
Force-Detected NMR for *In-Situ* Ananlysis

- Study single crystals, organic layers, and mineral phases from corers and drills
- Lightweight, low power;

  Can include multiple devices on one vehicle, or deploy in penetrators
- MEMS fabrication produces many devices at once ;

  Easy redundancy and feasible parallel analysis on and off earth

Sensitivity Comparison: Force-Detection vs. Inductive Detection

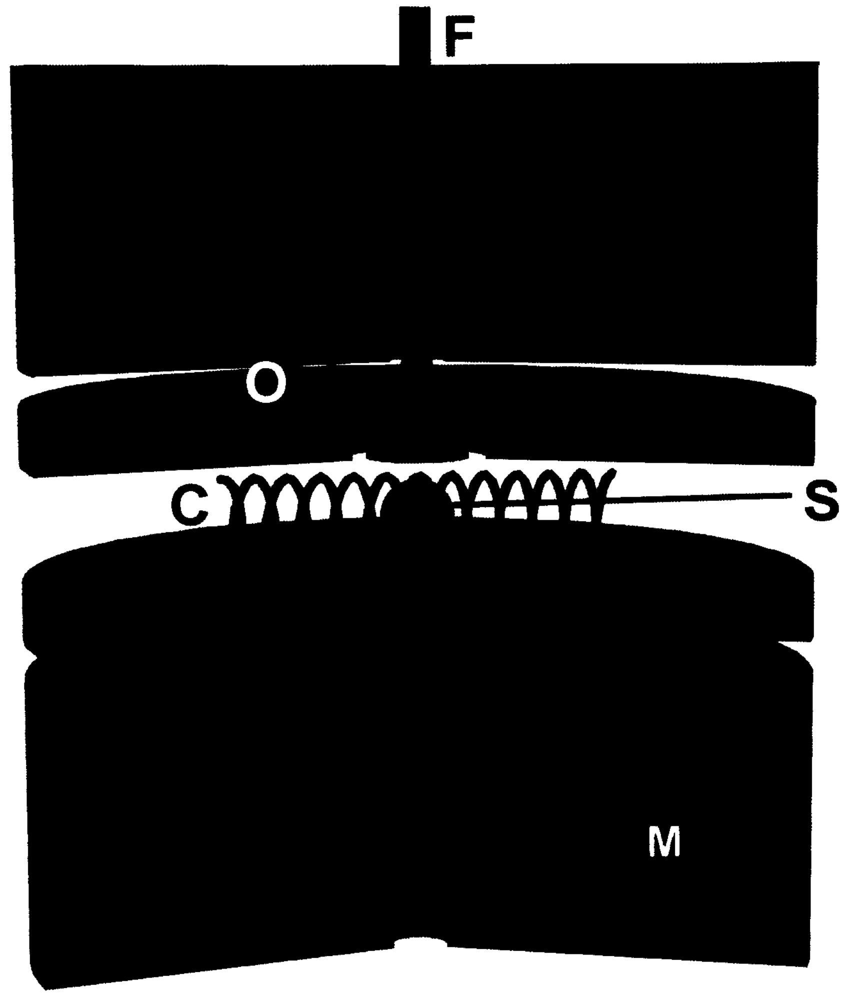


$$SNR_I = \frac{\textbf{Faraday-Law EMF}}{\textbf{Johnson Noise}} \propto r^2$$

$$SNR_F = \frac{\textbf{Magnetic Force}}{\textbf{Brownian Noise Force}} \propto r^{1/2}$$

Force-Detected NMR Spectrometer

- Detector magnet **D** mounted on Si oscillator beam **O** interacts with sample **S** via dipole-dipole *force*.
- Coil **C** applies rf excitation to sample **S**.
- Fiber-optic interferometer **F** detects oscillator motions.
- Ring magnets **R** provide homogeneous field across the sample.
- Permanent pole magnets **P** generate NMR ($\mathbf{B_0}$) field.

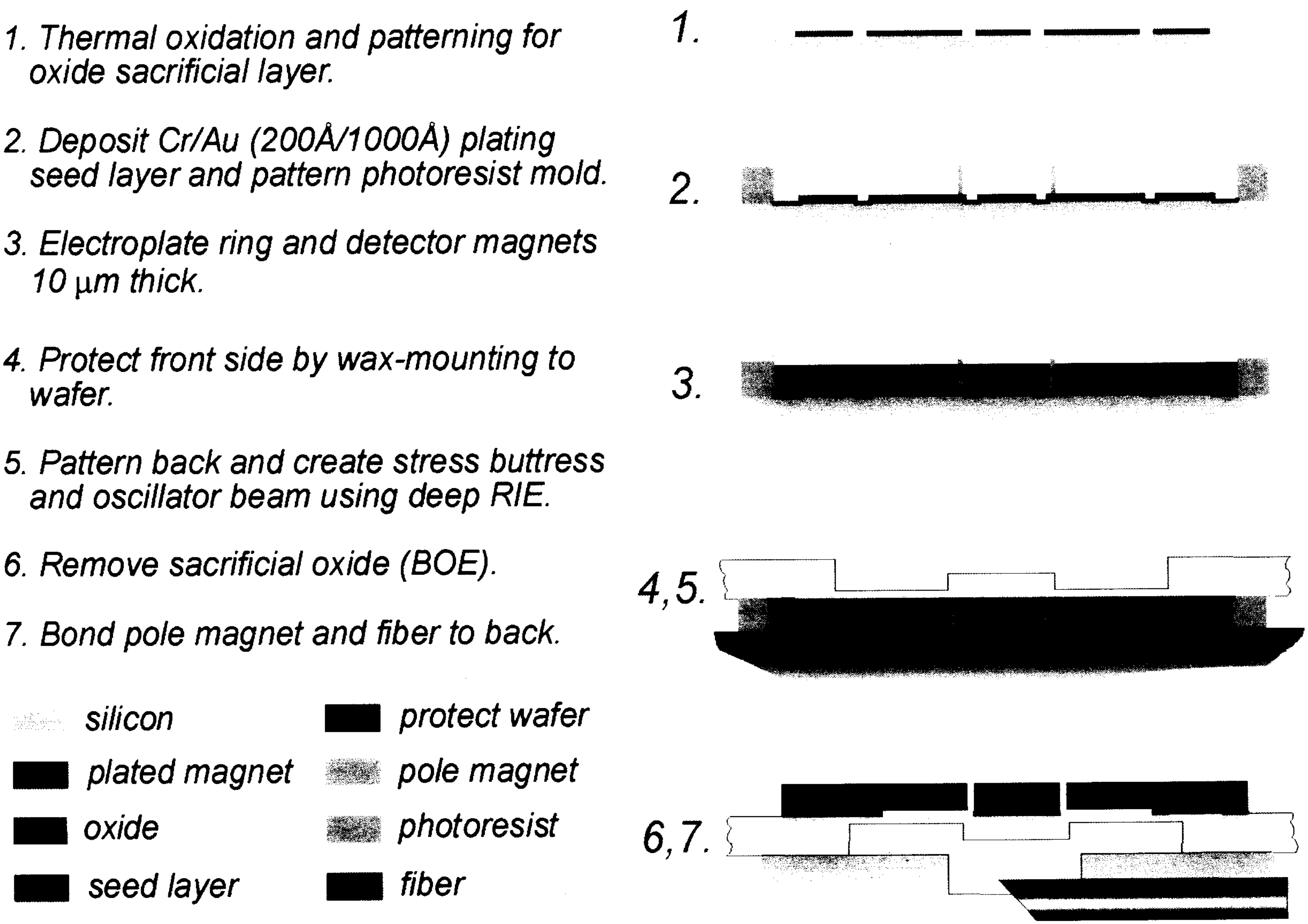


Design Goals for MEMS FDNMR Spectrometer

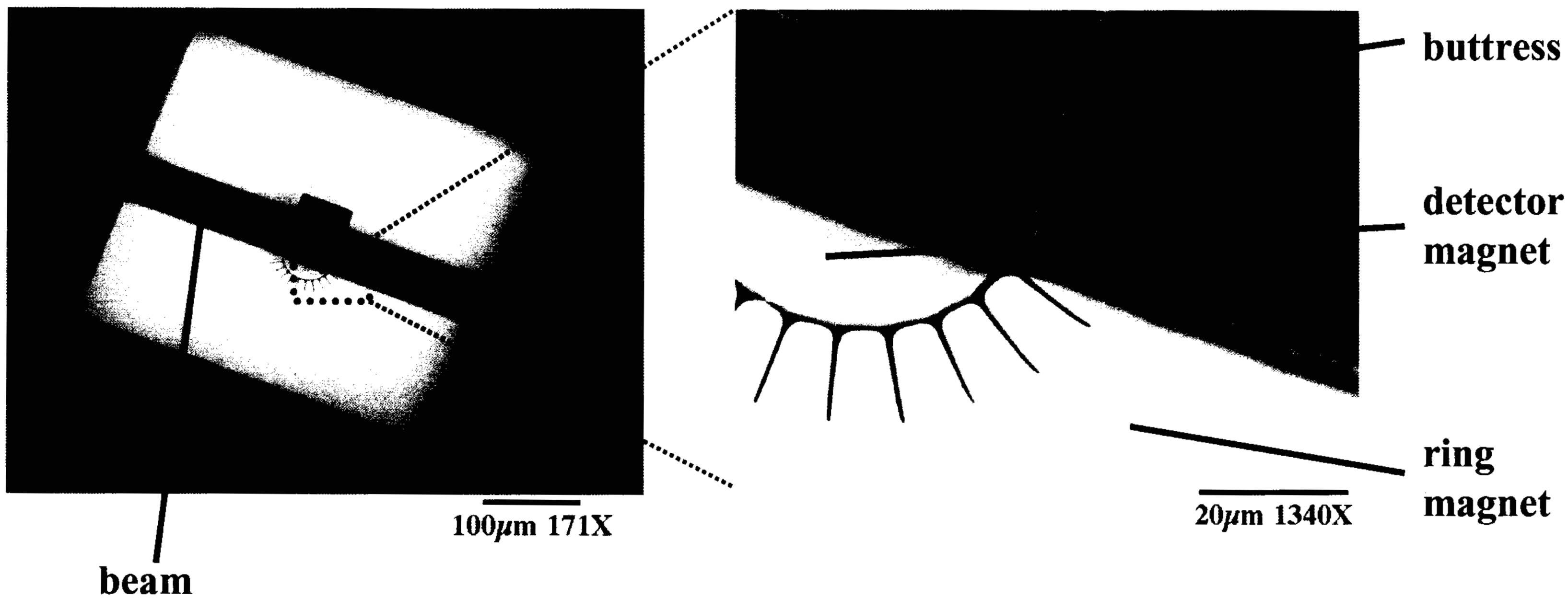
- B_0 ♦ 2 T
- Ambient temperature or cooled
- Optimize for 60 micron samples
- Total mass < 1g, power < 100mW, size < 1
  (single detector portable spectrom
- Field homogeneity better than ~
- □ ω_h ~ 1 kHz, τ_h ~ 1 sec (Q ~
- Single detector OR

Microfabrication Process Overview

1. *Thermal oxidation and patterning for oxide sacrificial layer.*
2. *Deposit Cr/Au (200Å/1000Å) plating seed layer and pattern photoresist mold.*
3. *Electroplate ring and detector magnets 10 μm thick.*
4. *Protect front side by wax-mounting to wafer.*
5. *Pattern back and create stress buttress and oscillator beam using deep RIE.*
6. *Remove sacrificial oxide (BOE).*
7. *Bond pole magnet and fiber to back.*

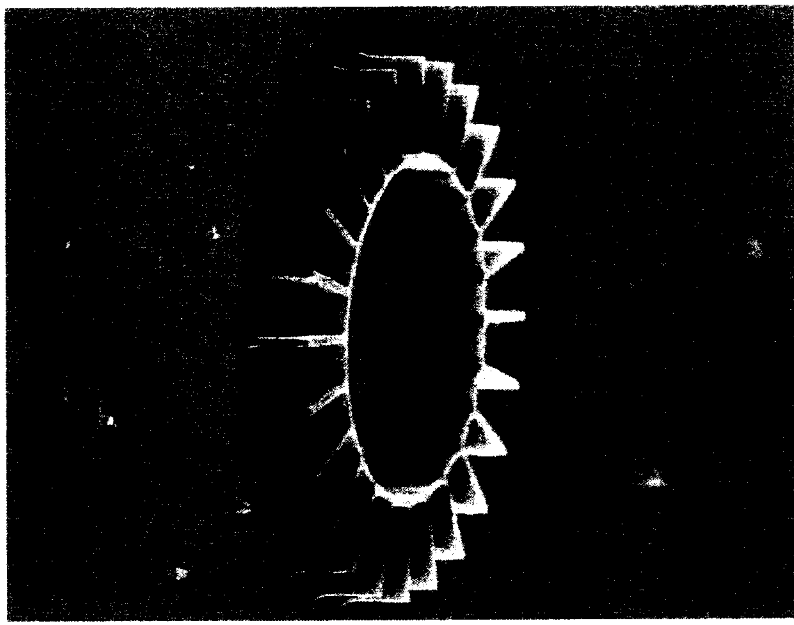


Deep RIE-Defined Beam with Plated Magnets

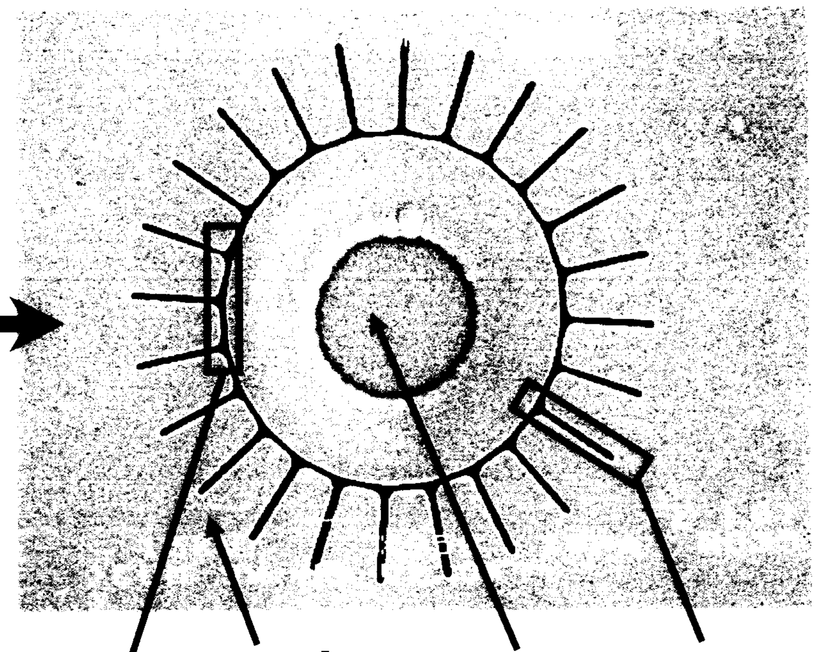


- Novel deep RIE process developed to define 2-6 μm-thick Si beam and stress buttress on backside of plated magnet array.
- After removal of PR and oxide sacrificial layer, a free standing beam with a detector magnet is formed. (υ_h ~24-166 KHz, Q~5000 at 50 mTorr)

Electrodeposition of Detector and Annular Magnets



high aspect ratio (10:1) PR mold



- The PR mold for electrodeposition defines 1 micron gap between detector and annular magnets and creates eddy-current-reduction slits.
- 10 micron thick 40Co:60Ni magnets (M_s = 1.2 T/μ_o, 40 Mpa stress) are successfully plated with the 1 μm gap and the slits.
- Co:Ni:Fe magnets with M_s = 1.8 T/μ_o on the way.

Conclusions

- There are many magnetic materials waiting to apply in magnetic MEMS.
- There are many problems to integrate these materials.
- More researches are needed to overcome engineering problems

Acknowledgements

UCLA
Prof. Ken Nobe
Mr. Morton Schwatz
Dr. D. -Y. Park
Mr. B.-Y. Yoo
Prof. Paulo Sumodjo
Prof. J. W. Judy
Prof. C.-K. Yang

JPL
Dr. Thomas George
Dr. Kyung-ah Son
Mr. Daniel Miller
Dr. W. Tang

Caltech
Prof. D. P. Weitekamp
Dr. L. A. Madsen,
Mr. G. M. Leskowitz

NASA Code R

DARPA MEMS Program:
DABT63-99-1-0020

NSF XYZ on a Chip